

NASA Human Spaceflight Scenarios Do All Our Models Still Say ‘No’?

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“All our models say ‘no,’ even models that have generous affordability considerations.”

-Elizabeth Robinson, NASA’s chief financial officer, 2011¹

Historically, NASA human spaceflight planning has included healthy doses of life cycle cost analysis. Planners put projects and their cost estimates in a budget context. Estimated costs became expected budgets. Regardless, real budgets rarely matched expectations.^{2,3,4} So plans would come and go as NASA canceled⁵ projects. New projects would arise and the cycle would begin again. Repeatedly, NASA schedule and performance ambitions come up against costs growing at double-digit rates⁶ while budgets barely rise a couple of percent a year. Significant skepticism greets proposed NASA programs at birth, as cost estimates for new projects are traditionally very high, and worse, far off the mark for those carried forward. In this environment the current “capability driven framework”⁷ for NASA human spaceflight evolved, where long term life cycle cost analysis are even viewed as possibly counter-productive.⁸ Here, a space exploration project, for example the Space Launch System, focuses on immediate goals. A life cycle is that of a project, not a program, and for only that span of time to a near term milestone like a first test launch.^{9,10}

Unfortunately, attempting to avoid some pitfalls in long-term life cycle cost analysis breeds others. Government audits have noted that limiting the scope of cost analysis “does not provide the transparency necessary to assess long-term affordability” making it difficult to understand if NASA “is progressing in a cost-effective and affordable manner.”¹¹ Even in this short-term framework, NASA realizes the importance of long-term considerations, that it must “maximize the efficiency and sustainability of the Exploration Systems development programs”, that this is “critical to free resources for re-investment...such as other required deep space exploration capabilities.”¹²

Assuming the value of long-term life cycle cost analysis, where due diligence meets reconnaissance, and accepting past shortcomings, the work here approaches life cycle cost analysis for human spaceflight differently.

- 1) If costs have traditionally been so high that adding them up is discouraging, are there any new facts on the ground offering paths to significantly lower costs?
- 2) If NASA’s spaceflight budget and process is an over-arching constraint, with its planning limitations favoring short-term outlooks, is there a way to step outside the budget box?
- 3) If life cycle answers have historically been too uncertain to be useful, is there a process where stakeholders gain valuable insights merely from emphasizing a common understanding around questions?

We analyze the potential life cycle cost of assorted NASA human spaceflight architectures – an architecture as a sum of individual systems, working together. With the prior questions of high costs, limited budgets and uncertainties in mind, public private partnerships are central in these architectures. The cost data for current commercial public private

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<https://science.ksc.nasa.gov/shuttle/nexgen/EZBio.htm>

partnerships is encouraging,¹³ as are cost estimates for future partnership approaches beyond low Earth orbit.¹⁴ Private capital, directly or indirectly, an ingredient of public private partnerships, may be a significant factor in finding a path around the limits of the NASA spaceflight budget. Also, understanding and reviewing the pros, cons and uncertainties of assorted architectures can assist in developing a common understanding around key questions as important if not more so than the numbers and answers.

Lastly, a scenario planning technique is briefly explored that can mature a common understanding about the agencies situation at hand and how diverse stakeholders can go forward together. Scenario planning, rather than focusing on answers, places emphasis on stakeholders developing a common understanding about the future. Putting aside costs, this is especially true of questions about sustainability and growth, results, benefits and expectations. While efficiency exercises or analysis look to reduce resources in one place to apply them elsewhere, moving around slices in a pie, scenario planning can get at the heart of the matter, growing the pie, transforming it, and making the pieces relevant. Especially important is the question of sustainability for different scenarios in the broad sense of the word – not just the narrow ability to survive or continue, but also the ability to adapt, prosper and grow.

Nomenclature

<i>AES</i>	=	Advanced Exploration Systems
<i>DoD</i>	=	Department of Defense
<i>DRM</i>	=	Design Reference Mission
<i>ET</i>	=	External Tank
<i>EUS</i>	=	Exploration Upper Stage
<i>ISS</i>	=	International Space Station
<i>JSC</i>	=	Johnson Space Center
<i>LCC</i>	=	Life Cycle Cost
<i>LEO</i>	=	Low Earth Orbit
<i>LM</i>	=	Lunar Module
<i>NRC</i>	=	National Research Council
<i>PPI</i>	=	Purchase Price Index
<i>R&D</i>	=	Research and Development
<i>SCaN</i>	=	Spacecraft Communications and Navigation
<i>SFS</i>	=	Space Flight Support
<i>SLS</i>	=	Space Launch System
<i>SRB</i>	=	Solid Rocket Booster

I. Introduction

This paper's essential idea is that when NASA's space exploration ambitions and cost inflation exceed the rate of NASA budget growth over the long term, the result is ever-larger scale programs that stretch increasing efforts across longer time spans and this distribution of funding causes increasing NASA irrelevance. With distance to a moving target increasing over time, hitting the target may be merely challenging today but impossibly difficult tomorrow. Reducing ambitions, aiming for closer targets, merely reinforces the irrelevance the new plan tries to avoid while creating unsustainable¹⁵ scenarios, programs stretched so far across time the low flight frequency calls into question the ability to maintain competence and safety. Irrelevance is the likely loss of stakeholder interest¹⁶ as much as a certainty of being overcome by events as planned results stretch beyond a generation. We propose a steady transformation of NASA space exploration and operations funding towards more, smaller commercial / public-private partnerships, favoring those with strong non-government business cases, to increase the pace of NASA achievements and avoid having most funding in projects with goals forever a generation away. A stakeholder should be able to begin and end at least one major program and see its goals achieved, and preferably more, within a single career, rather than handing off incomplete tasks to another generation with those goals still a generation away. We will show this approach realizes even greater agency exploration ambitions over the long term creating a sustainable, dynamic environment that avoids entrenched positions incapable of staying ahead of budget curves, while creating the stakeholders necessary to sustain the budget commitments NASA requires.

Life cycle cost analysis is required to explore multiple possible outcomes, costs and budgets all together over the long term. Nonetheless, long term NASA cost analysis has history, not all of it good.

Arguments against long-term life cycle cost analysis in NASA spaceflight projects point to the practical, historical difficulties experienced. The longer-term an outlook, the more uncertainty. Life cycle cost analysis can seem premature or counter-productive from this point of view. Avoiding “sticker shock”¹⁷ becomes a reason to avoid getting too far ahead in life cycle cost analysis. Because of uncertainty, a life cycle cost, as a sum of all project costs over many years, can quickly become a trivial analysis with a total equal to the sum of NASA’s spaceflight budgets over that time and only weakly linked to the details of potential plans or benefits. Assuming a more generous budget than in the past, the life cycle cost goes up, not down. A good thing, more budget, becomes a bad thing, more cost. NASA’s current “capabilities driven framework”¹⁸ would seem to address this tension, defining what’s near, methodically taking things one step at a time - learning to walk, we worry later about running. Along the way, the approach may “allow the perception of policymakers to naturally reorient to the reality of the current space exploration efforts.”¹⁹

Unfortunately, attempting to avoid some pitfalls in life cycle cost analysis breeds others, as noted in audits – neglecting to look long term with appropriate life cycle cost analysis “does not provide the transparency necessary to assess long-term affordability” making it difficult to understand if NASA “is progressing in a cost-effective and affordable manner.”²⁰ The cure proves worse than the disease. The dilemma remains, that “NASA’s human spaceflight budget has been able to afford one or two modestly-sized programs at a time.”²¹ Nonetheless, human deep space exploration requires an assortment of new projects that together go well beyond a single new program, and well beyond “modestly-sized”. It’s been observed that when exploration approaches depend on adding ever more layers of cost to NASA’s budget even adding money just delays re-entering the same trap. Then “you are right back where you started, the budget crashes, you can’t afford to build the new thing without cancelling the old thing.”²² All this is a complicated way of saying that NASA deep space exploration has to add-up, costs, budgets and advertised outcomes. An approach resigned and focused on taking it one day at a time, while seeming practical, does not help make the numbers more likely to add-up eventually.

The motivation for the analysis that follows is NASA’s ambitions, which are unsustainable in a world where projects have too long seen costs growing at double-digit rates while budgets barely rise a couple of percent a year. Chopping trees faster than they grow works for a while, filling yesterday’s orders for lumber, but eventually reality will intrude. As observed of NASA projects – “If we do not think creatively about this crisis we will all be competing for the one place at the shrinking water hole.”²³

There are three questions of special interest here:

- 1) If costs have traditionally been so high that adding them up is discouraging, are there any new facts on the ground offering paths to significantly lower costs?
- 2) If NASA's spaceflight budget and process is an over-arching constraint, with its planning limitations favoring short-term outlooks, is there a way to step outside the budget box?
- 3) If life cycle cost answers have historically been too uncertain to be useful, is there a process where stakeholders gain valuable insights merely from emphasizing a common understanding around questions?

Understanding questions is important, before considering possible answers.

On high costs, public private partnerships offer a potential path to reduce costs significantly for NASA’s deep space exploration systems. Although current partnerships like the commercial cargo and crew services to the International Space Station (ISS) have gone only as far as low Earth orbit (LEO), there is no NASA cut-off point at LEO for public private partnerships. As advocates in this area have said - “the artificial boundary being discussed in Washington makes no sense”.²⁴ Estimates for deep space systems using public private partnerships will primarily address the obvious, avoiding a strategy based on an assumption of high costs for deep space systems, strategies that then avoid the very systems required.

On budget constraints, by relation, as we break out of the box of assuming high costs (and schedules with no end) we also look at how to break out of the box of limited budgets. Other studies addressing the poor budget outlook for NASA have chosen to avoid this topic, assuming an increase in the NASA spaceflight budget, a *deus ex machina*, but at the start of the story, or at least assuming NASA’s budget keeps up with cost inflation. We do none of that here, assuming future budget growth from past budget trends. As reconnaissance, we analyze if NASA spaceflight can

achieve greater results within this budget constraint with new approaches, alongside the addition of a second set of books, private capital attracted to the space sector at the intersection of NASA needs and private enterprise.

Since perhaps the strongest reasons against long-term cost analysis are uncertainties, the work here emphasizes questions for understanding uncertainties, rather than attempting to eliminate these. To address usefulness vs. uncertainty, we emphasize questions, context and a relative sense of direction instead, not absolute predictive answers. We recommend trades that compare numerous options, rather than one that focuses on a chosen point design stemming from prior decisions. This approach can offer a sense of direction for decision makers and stakeholders apart from absolute predictive confidence in the numbers. Precision (consistency), looking across many options, can prove valuable to support decision making even when accuracy (correctness) is still maturing. The purpose is not to choose a specific option, instead surfacing characteristics of preferred options to steer investments. As well, the process of analysis helps stakeholders understand fundamental questions. Questions that might have seemed clear can suddenly appear ill defined once analysis ensues.

The analysis that follows explores the life cycle cost of many scenarios, choosing none, to understand these relative to each other, using results to understand a variety of fundamental questions.

II. A Brief History of NASA Life Cycle Cost Analysis

NASA life cycle cost analysis has a rich history. Represented as charts of costs against time, often with the assumption that budgets would cover costs, the look and feel of LCC analysis has varied surprisingly little over time. NASA was already laying out plans in 1969 for a Mars mission by 1986 (Figure 1). The Space Task Group reported to the president “NASA has the demonstrated organizational competence and technology base, by virtue of the Apollo success and other achievements, to carry out a successful program to land man on Mars within 15 years”. These plans would not happen, as a review noted decades later “The air of inevitability that hung about a manned Mars mission in the wake of NASA’s 1969 triumph was largely imagined” and “NASA either could not or would not understand the importance of complying with the budgetary process.”²⁵ Budget advocacy entangled with budget planning suffered the first in a string of LCC disconnects seen many times to follow.

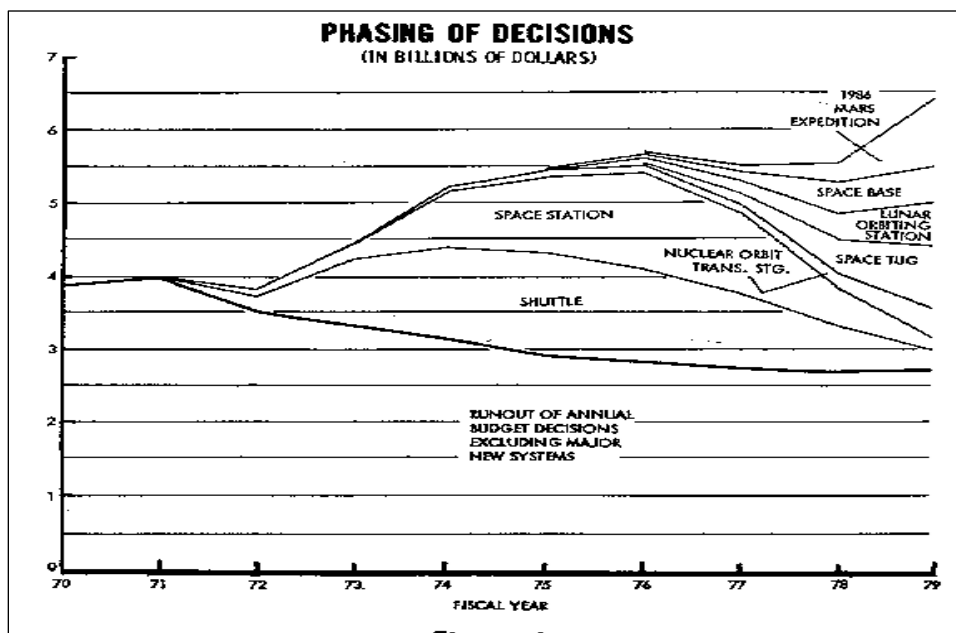


Figure 1. The 1969 life cycle cost outlook from the Space Task Group Report to the president.²⁶

A generation after the Space Task Group report, NASA again had a sand chart laying out a course for the future, with space systems, costs and budgets laid out through 2020. Now it was a return to the Moon, not Mars. Plans called for a relatively small initial budget increase (\$250M per year for 4 years). After that, NASA's spaceflight budget would again have a feature not observed in the wild - the budget would keep up with cost inflation. Construction of the multi-billion dollar ISS wasn't even finished, but the plan addressed the station's demise – it was to be de-orbited a mere six years after completion. To help the picture more, the plan had another feature never observed in the wild; the space station's costs through its short life would not increase.

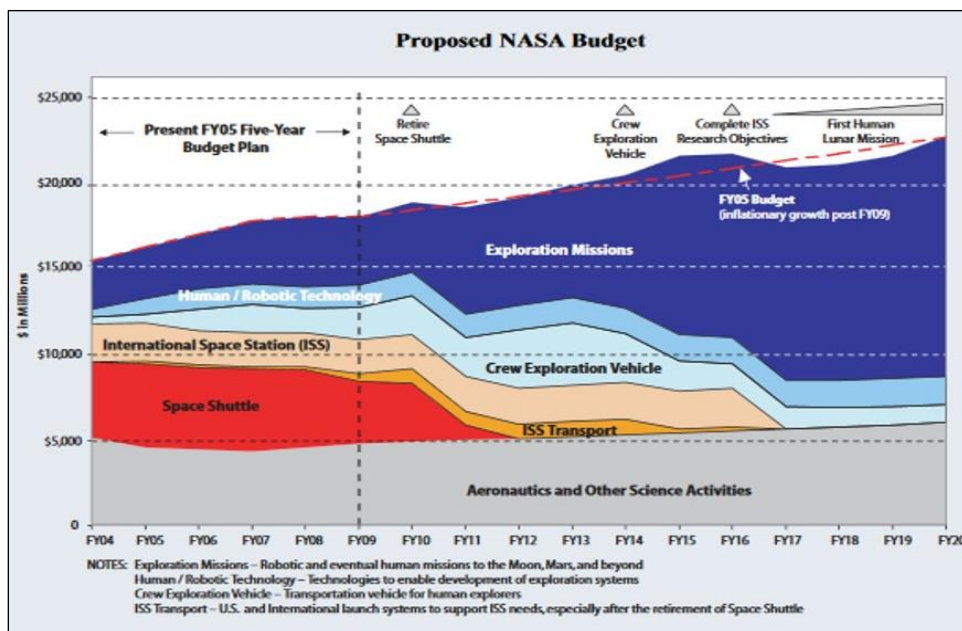


Figure 2. The 2004 proposed NASA cost/budget outlook in another report to the president, after the loss of the Space Shuttle Columbia.²⁷ Again, a life cycle view combined expected costs, budgets and assumptions into a long-term outlook to achieve an outcome, landing a crew on the Moon.

The 2004 cost/budget outlook for a return to the Moon became the Constellation program, with a review committee appointed by the president 5 years later. Again, recognizing the magnitude of the sum total of all costs to achieve an outcome, here a return to the Moon, the 2009 review stated –

“Over the next 10 years, NASA is scheduled to devote \$99 billion to the nation’s human spaceflight program. In recognition of the magnitude of these planned expenditures, coupled with questions about the status of the current human spaceflight program, the White House Office of Science and Technology Policy, as part of the due diligence of a new administration, called for an independent review of the present and planned effort.”

Sand charts followed looking at many scenarios, with the committee concluding - “Either additional funds need to be made available or a far more modest program involving little or no exploration needs to be adopted.” With Sally Ride leading the unenviable^b task of life cycle cost analysis for different scenarios, the same problems arose as seen many times before. “Exploration doesn’t appear viable under the FY10 budget and run-out.” Figure 3 was emblematic of the problem, just one of many scenarios that did not add up, with life cycle costs far surpassing the foreseeable budget.²⁸

^b “I think it’s fair to say that our review group drew the short straw, and I drew the shortest by having to actually do this presentation.” Sally Ride, 2009.

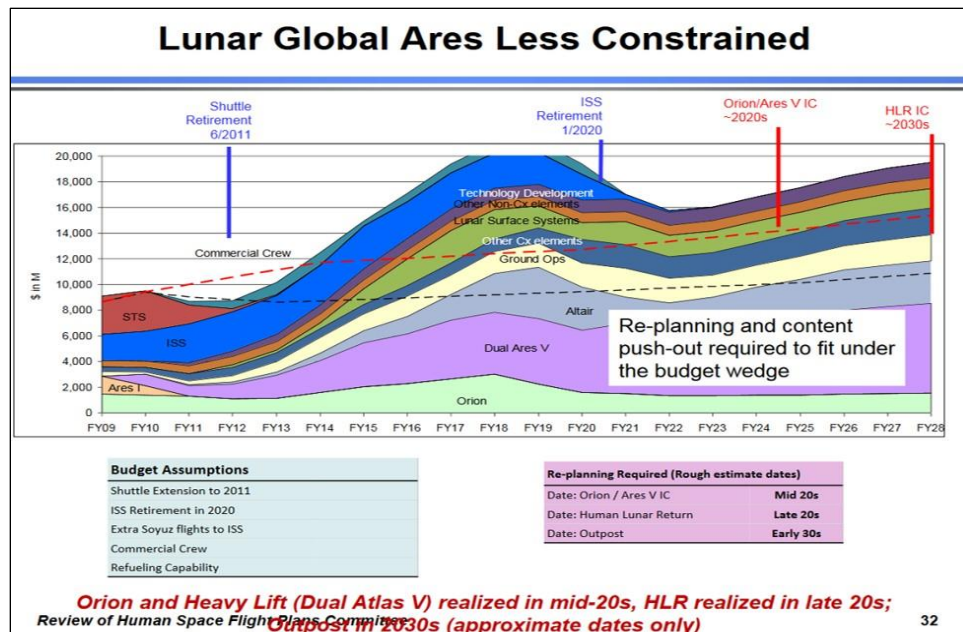


Figure 3. A 2009 life cycle cost scenario, one of many by the Review of Human Spaceflight Plans Committee. The dashed red line is a limit the layers of estimated costs cannot exceed, an estimate in its own way also, of likely available budget funds.

The 2009 Human Spaceflight Committee sand charts did not arise in a vacuum. The program of record, the Constellation program, tracked costs vs. budget for its systems. Constellations analysis revealed again that estimated costs and expected budgets did not and would not match up.^{29,30} The following critical planning assumptions by the Constellation program would all prove incorrect (many traceable to the earlier 2004 Presidential Committee) -

- 1) That the end of the Shuttle program would cause an immediate and sizable increase in funding available for the Constellation program, as in the 2004 Aldridge report³¹
- 2) That the end of the ISS in 2016 (sooner rather than later), would cause another immediate and sizable increase in available funding for the Constellation program, as in the Aldridge report³²
- 3) That funds from elsewhere in the agency would be redirected to Constellation
- 4) That the NASA budget would increase at a rate equal to cost inflation

Rather, NASA's operational space transportation funding, what was the Space Shuttle program, would immediately be needed in new programs outside of Constellation to support the ISS. These programs became the public private partnerships for cargo and crew to the ISS. The ISS yearly development (construction) funds would become the yearly operations and maintenance budget. In addition, now operational, the ISS required research funding to use the facility beyond maintaining it. Redirecting other funds, meager as these were, slight shifts in funds from the Science arm of NASA to the Spaceflight arm, would see increasing backlash. Shifting funds to manage the life cycle cost/budget disconnect of a return to the Moon meant, "forcing everyone to be the enemy of [Constellation]...undermining the kind of unified scientific support that you need to be able to sustain a program of this scope."³³

In 2010, the White House canceled the Constellation plan to return to the Moon and a redirection of NASA's post-Shuttle plans followed. While major elements would remain, the end of Constellation would mostly mark the end of official NASA human spaceflight life cycle cost sand charts and related cost analysis.^{34,35,36} Nonetheless, emphasizing the importance of a life cycle cost perspective for long term planning would continue elsewhere. In 2011, Human Spaceflight Review committee member Greason would use sand charts (Figure 4) to observe how strategies that rely on adding ever more layers of cost, cost which simply flat-line and persist, "don't achieve the goal of settlement."

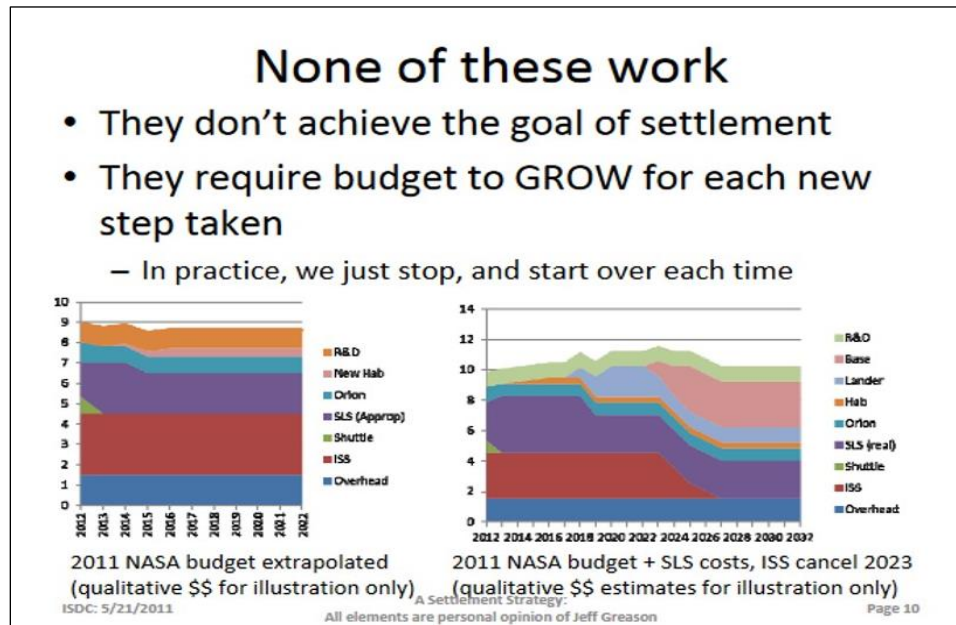


Figure 4. In 2011, Jeff Greason's observation about strategies where life cycle costs never add up to results.³⁷ From "A Settlement Strategy for NASA, Keynote Address" by Jeff Greason. Used with permission.

A critical distinction is required, that the flat-lining of costs, the behavior of rising to a yearly level and then persisting at that level for a long time even as a project is finished development and goes operational, is not itself a flaw. A strategy adding more and more layers of cost over time for increasingly ambitious results can go down at least two paths to avoid budget pile-ups. These possibilities include:

- 1) Reducing yearly operational costs significantly over whatever yearly costs were seen during the programs up-front development
- 2) Reducing the yearly level of costs significantly all years for any layer (any system)

Or in any version of the prior two factors, increasing productivity radically, achieving more and more every year for any level of funding or even with declining funding.

The 2009 Review of Human Spaceflight Committee made special note of possibility 1, where a project being finished, its operational costs are much less than what it took to get there. The committee's notional sand charts in Figure 5 describe this. Current large-scale projects like the Space Launch System (SLS) may even incorporate this notion into long-term thinking to get the current yearly budget to drop by more than 50% once operational, at the same time launch rates increase.³⁸ Unfortunately (as with the notion of budgets keeping up with inflation) NASA has not observed this cost behavior for spaceflight projects in the real world - yet.

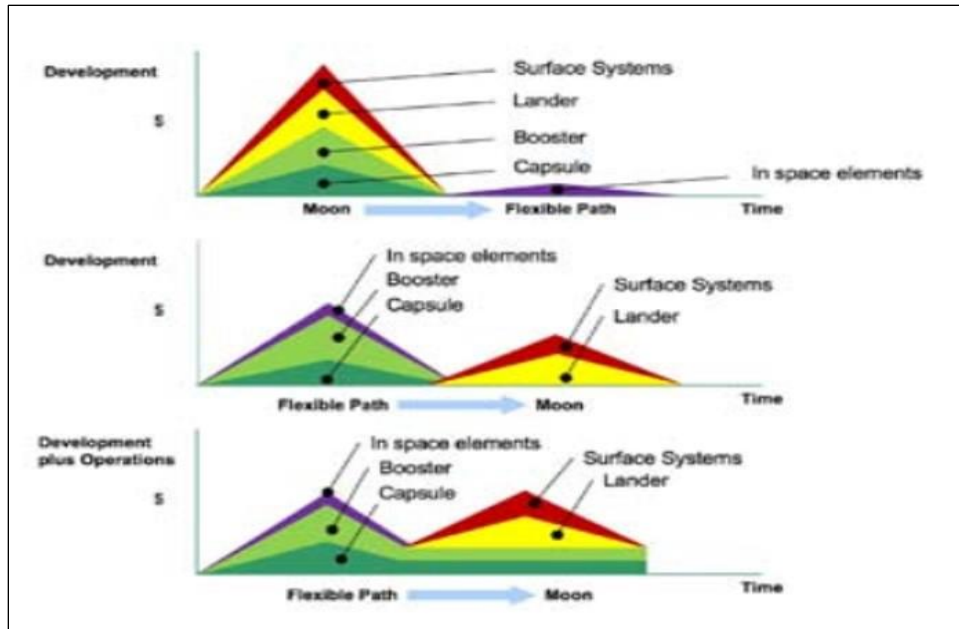


Figure 5. From the 2009 Review of Human Spaceflight Plans Committee.³⁹ For the case shown in the lower figure “Development plus Operations”, *IF* after developing a system its operational costs drop significantly, *THEN* the development of additional capabilities can begin.

It’s in this context, not only as assorted space exploration cost and budget analysis failed to add up, but as fundamental planning approaches and assumptions across NASA’s spaceflight projects proved incorrect, that in 2011 NASA’s Chief Financial Officer said, “All our models say ‘no,’ even models that have generous affordability considerations.”⁴⁰ The “generous affordability considerations” were not new. Independent reviews have put a “culture of optimism” at the top of the list of reasons for NASA’s “historical inability to consistently meet project cost, schedule, and performance goals.”⁴¹ However, even this traditional cure-all of “generous affordability considerations” could not work its magic by 2011. No scenario added up to say ‘yes’.

From 2011 to date, the inability of any path forward to add-up lead NASA to the “capability driven framework” where the long term plan became a series of broad notions - “*Journey*, not destination”⁴², “A capability driven framework will *enable* affordable and sustained human spaceflight exploration,”⁴³ and “Mars: Ultimate human destination in the next *decades*.”⁴⁴

Inevitably, a 2012 National Research Council (NRC) review of NASA’s strategy noted that “While a capabilities-driven approach may be the most reasonable approach given budget realities, such an approach still has to be informed by a clear, consistent, and constant path to the objective.” This NRC review recommended four options - improving efficiency, more partnerships (international and public/private), more funding and reducing NASA’s scope.⁴⁵ Three of the four NRC recommendations are the usual suspects seen before – efficiency (reducing future costs for a given outcome), increasing the NASA budget and moving funds around in the budget. The emphasis on partnerships is a newer factor.

In 2014, another NRC committee analyzed NASA’s exploration life cycle costs building on the prior 2012 NRC committee. The basic tenet of a capabilities driven framework was sound, small “building blocks to be assembled in various configurations that allow the changed goals to be addressed without analysis *ab initio*.”⁴⁶ “Multi-use, evolvable space infrastructure, minimizing unique major developments” was a strategic principle.^{47,48}

Here we see an attempt to get NASA’s human spaceflight costs, budgets and outcomes to add up using the same features observed in the sand charts of 1969 and 2004 (and many in-between), but again, features not observed in the wild. In Figure 6 we see (1) reductions in yearly operations costs vs. yearly costs during development (Orion after 2018 and SLS after 2020-ish upgrades), (2) a shift of funds from one part of the spaceflight portfolio to another (ISS budgets are frozen after 2018, even as NASA’s budget topline increases), (3) a budget increasing at 2.5% a year, (4) meaning new projects receive funding at a rate faster than inflation, and (5) (in subsequent figures) moving 100% of the ISS funds post-termination to deep space exploration. All of these planning features were also in earlier sand charts, in 1969, 2004 and 2009 Constellation program planning. The 2014 NRC committee life cycle charts, limited to the assumption of an SLS launch vehicle,⁴⁹ also assumed “As long as flat NASA human spaceflight budgets are

continued, NASA will be unable to conduct any human space exploration programs beyond cis-lunar space. The only pathways that successfully land humans on the surface of Mars require spending to rise above inflation for an extended period.”⁵⁰

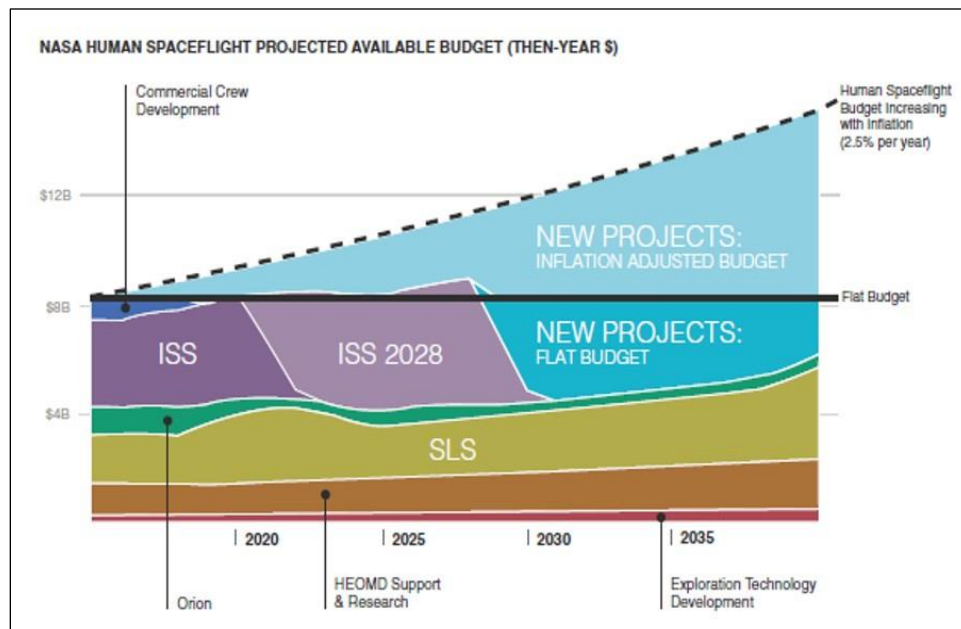


Figure 6. The 2014 National Research Council sand chart of a possible NASA exploration path. Two projected available budgets are shown, flat or increasing with inflation.

Even with these traditional, favorable assumptions, the 2014 NRC review placed the earliest crewed surface mission to Mars around 2040-2050, with that being “optimistic”.⁵¹ This creates a dilemma, whereby even scenarios that might add up with traditional, generous assumptions suffer a new and significant flaw. Now the mission tempo and associated production, launch and operations rates go so low as to bring into question how the whole enterprise maintains proficiency, capability and expertise in tasks it will do so un-often – by plan. In addition, with goals so far, there is no urgent connection with what goes on today.

NASA plans have suffered common flaws. In practice there are usually layers of cost that start high, going higher as time goes by and surprisingly even once development finishes and systems go operational. Adding funds to these first steps entrenches funding there that is required for the next steps. The ability to fund next steps from the existing budget disappears. The funding is required 100% by previous steps. In a productive sense, the prior project even places a lien on more than 100% of the prior funding. This is actually possible, as previous steps never fully achieve their original goals. If new funding does appear, much work remains in the steps thought finished. Since next steps complete the plan, but there is no more funding, NASA does not achieve its advertised goals. The big picture does not add up.

It’s been documented how disregarding past behavior is used in attempts to get the predicted life cycle costs of assorted space exploration plans to add up - to fit into foreseen budgets, where system costs drop once operational where budgets rise at least with inflation, or even more generously.

While many life cycle cost analyses are endeared of the notion of budgets rising with inflation, it’s worth asking what are useful assumptions, what is *plannable versus wishful*. In planning, hoping for the best does not mean ceasing to prepare for the worse. The related tactic, moving money around in the NASA budget, either for ongoing projects or future ones, has also run into repeated difficulties. The end of the Shuttle program did not result in a wholesale transfer of its budget to the new Constellation initiative. This makes rigorous review a requirement for any such assumption going forward, like with the notion that 100% of ISS funding is available for deep space exploration systems when that program ends. Assumptions that appear to be common sense have proven to be much more complicated.

Most recently, NASA purposely avoids⁵² life cycle cost analysis, creating a situation pointed out by cost estimating subject matter experts - “If management doesn’t really want to know the truth, that fact flows down to the estimating community pretty quickly in the form that quality estimates aren’t an important product anymore”.⁵³ This begs defining an alternate approach for life cycle cost analysis and its role in planning.

III. Methodology

Life cycle costs analysis must move beyond the issues identified previously. Common issues affecting the credibility of prior life cycle cost analysis fall in the category of poor assumptions. Five poor assumptions occurring repeatedly - where tomorrow is always different from today - are:

- 1) Budgets grow at a rate not supported by historical data while costs increase at a rate equal to budget growth, even though aerospace and space systems cost inflation is poorly understood.
 - Never addressing independently how the costs of a basket of NASA goods – systems, technology, products or services – has varied over time.
- 2) Annual operations budgets for a system are always much less than its annual development budgets.
 - Since the days of the Space Task Group in 1969, assuming significant new funds will appear after a major spaceflight development is complete and operations begin has not proven true.
- 3) One hundred percent of the funding from another program ending is available to another beginning.
 - History would indicate this assumption requires rigorous review, contrary to the nature of a simplifying assumption. What kinds of funding become available (procurement dollars, personnel dollars), with what latitude to move to other projects (specifically, other organizations and companies), and how far away (a measure of the chance of being overcome by events) are useful questions.
- 4) NASA Human Space Flight (HSF) is the #1 NASA priority.
 - By relation, funds are easily moved in analysis as required (“in theory”), not just within HSF, but also from very long term research and development (R&D / technology) into current full scale developments, or into operations, and even from outside HSF, such as NASA Science or Aeronautics into NASA HSF.
- 5) Optimism – new programs are always different – a common, poor assumption that’s often necessary when past data points are so expensive they would never yield attractive new data points unless *this time is different*.

The temptation may be to categorize all these assumptions under the last item, optimism. However, evidence suggests there are many more incentives and complex motivations behind poor planning assumptions well beyond mere optimism or a “can do” culture among NASA and its industry partners. Reviews of cost over-runs in the US Department of Defense (DoD) note “the well-known bureaucratic power game of front-loading or buying-in.” Once early funding is spent, this “in effect, gives the contractor permission to use public money to build his political protection network by systematically spreading subcontracts and production facilities to as many congressional districts as possible.”⁵⁴ Inevitably the low operational or per unit costs never materialize as their purpose was only to justify and entrench the early up-front costs. A full analysis of the real reasons behind all these poor assumptions is beyond the scope of the work here, but we can perform life cycle cost analysis that mostly avoids these assumptions.

More recently, there is the life cycle cost issue of *uncertainty*, not about cost estimates for complex systems over many years, but as a justification to avoid performing cost analysis in the first place. Ironically, an advocate of this position might rely on historical data, to avoid optimism – if life cycle cost analysis has been unproductive, often the nails in the coffin on NASA’s plans, NASA should avoid long-term cost analysis.^{55,56}

The only optimism here is the assumption it is possible to overcome past shortcomings in life cycle cost analysis and identify options for NASA space exploration that avoid ever-higher costs and diminishing prospects - within a productive analytical framework. Beyond GAO audits affirming NASA *must* look long term with appropriate life cycle cost analysis to provide the transparency necessary to assess long-term affordability, we optimistically assume such work can be productive and useful across many stakeholders.

Therefore, the basic tenets to our life cycle cost methodology are –

- *Go with history in assumptions*
- *Go with reference data in cost estimates; understand the state of the art*
- *Assume life cycle cost analysis can be productive and useful to many stakeholders*

Specifically, the assumptions in this analysis are the opposite of the usual suspects –

- 1) Budgets will increase only at their historical rate, here at 1.95% a year, from data going back 15 years and project costs will increase at the rate published in the NASA New Start Inflation Indices, 2.5% a year.
 - By relation, NASA will continue to lose purchase power, as it has historically (a 9% loss of purchase power since 2003).
 - It's important to note that certain approaches explored ahead may get around this decline in purchase power, for example when costs drop significantly or results increase significantly, or both, for a given budget. These approaches are deflationary, increasing purchasing power over time.
- 2) Annual budgets for space systems will be about the same in later operations as during earlier development.
 - NASA projects and acquisitions historically favor stability, not roller coaster rides.
 - Costs are not benefits. Benefits are a separate issue of productivity, what you get for a cost such as outcomes by a certain date.
- 3) Historically, ample doses of skepticism and rigorous assessment must accompany any notion that funding from one program ending might become wholly available to fund another.
 - Although counter intuitive, as a program ending that cost \$X dollars per year must free up that money when it no longer exists, historically this seemingly simple assumption has proven to be close to counting chickens before they hatch.
- 4) Avoid moving money around and across accounts, or making assumptions one area remains flat while another grows much faster.
 - Historically, transferring funds around in NASA is not just difficult, it creates the issue of making everyone who loses funds the enemy of the project receiving funds, undermining the kind of support needed to sustain new programs. The assumption that NASA's portfolio mix must inevitably change at the level of directorates, or R&D vs. development and operations, is avoided in this analysis as an unnecessary complication that is also useless for predictable, actionable long term planning purposes.
- 5) Let reference data speak for itself (a leaning to "reference class forecasting"⁵⁷)
 - This helps avoids the bias of optimism. Stick with history as it applies by similarity, bad and good.

Item 1 really contains two unrelated matters. Cost inflation is an area ripe for rigorous assessment, asking how the cost of the basket of goods of human space flight systems has increased over time and how it might increase (or even decrease) in the future. Although often treated as the same assumption, cost inflation and budget growth rates used for planning are generally unrelated. To make matters more complicated, budget advocacy often goes on the record as budget planning. Perhaps one day the definitive work on how costs have inflated for the basket of goods of NASA's human space flight systems will be published. Then the data will be married to the common assumption that NASA's space flight budget will keeps up with that number. Perhaps the data will show space flight system costs have inflated at 7% a year since year X, on a trend line that's dropping to 5%? Budget requests will ask for a 5% increase on this basis (or whatever the number is). Otherwise, if budget growth is tied merely to economic growth ("Implementable in the near term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth."⁵⁸) before long NASA will have to request budget cuts – to be consistent. There are many moving parts to this assumption. Cost growth and cost inflation are difficult topics at best.^c

^c A recent GAO audit (GAO-15-320SP) of major NASA projects calculated "cost growth" at 2.4%, but cost growth is not cost inflation; it does not help estimate how much more expensive a thing will be the next time around, only how much more a thing cost versus what was planned – plans that already included a factor for inflation. The Purchase Price Index (PPI) for Aerospace (<https://fred.stlouisfed.org/series/PCU3364133641>) stands at 230 (100 baseline), an average inflation rate of 2.63% (since 1985). There is no index specific to space systems. *Deflation* is seen in public private partnerships like the ISS commercial cargo program, where using historical costs would have given a cost estimate far above actual experience (NASA Commercial Market Assessment for Crew and Cargo Systems). In NASA Science, Elvis calculated project cost inflation at 10% a year for astronomy missions and 15% a year for Mars landers. A defense focused look at this topic concluded "The use of the GDP deflator to measure price increases for all elements of DoD procurement, including all Major Defense Acquisition Programs (MDAPs), is *inappropriate*. The GDP deflator may empirically be a reasonable proxy for procurement inflation overall, but it does not allow the Department to capture differences between, for example, ships, aircraft, and vehicles. However, the initial examination provided here does not clearly indicate what alternative indexes would provide better estimates of inflation for procuring the various types of systems."

Item 3 above is especially important. Deep space exploration and the funding available from the end of the ISS are repeatedly linked in assessments. With the Shuttle program ending, an analysis would have thought Space Flight Support (SFS) costs would drop. Instead, that budget line *increased*. The end of the Shuttle program revealed costs that were not uniquely Shuttle specific. Also revealed - these funds were not available for new work. The entwined nature of ISS Operations and Johnson Space Center (JSC) Mission Operations (all apart from ISS R&D and crew and cargo transportation) presents similar challenges today. Quite possibly, not all funding from the end of one program (the ISS) can be assumed available to develop new capabilities, systems or hardware.

Item 4 also requires special attention. Inevitably, there will be changes in the mix of the NASA portfolio, the percent of the budget in R&D vs. more mature or mission focused development / operations, in Aeronautics vs. Science or vs. Human Space Flight. As these changes are not predictable, and small changes are not significant, the analysis here avoids complicating the analysis with these kind of transfers.

The goal here is to explore the life cycle cost of many scenarios, choosing none, to understand these relative to each other, using results to understand a variety of fundamental questions. There are uncertainties specific to each scenario's mix of projects, technical, cost and outside factors. However, relative comparisons between scenarios can inform all stakeholders about NASA's future path.

Sustainable scenarios for human space flight and deep space exploration may well depend on assumptions ingrained with healthy doses of realism informed by history.

Having covered assumptions, the methodology of the life cycle analysis that follows strives for clarity, leaving little unsaid about a scenario by virtue of placing every scenario into the bigger picture. To questions like "what happens with R&D" – a look at the graphs shows this item (AES) has been left unaffected, proceeding on a budget trend consistent with a linear extrapolation from current year data. We avoid loose threads. This also goes to one characteristic of a good model, falsifiability.⁵⁹ If a life cycle analysis leaves too much unaddressed, predicting vague costs of elements in a backdrop that is also vague, lacking context, that vagueness makes it possible to say roughly anything as it turned out went just as planned. The model ceases to make falsifiable predictions that analysis can evaluate after the fact (i.e., no take backs), while also ceasing to be truly *plannable*. (For example, the life cycle scenarios in Figure 1 and Figure 2 were comprehensive enough to be falsifiable).

Principally the methodology for human space flight analysis relies on a view of the whole chessboard, shown in the "blank" template in Figure 7.

- **\$ Space Flight Support (SCaN et al) + \$ R&D/AES:** Space flight support and exploration R&D are at the top of the budget layers, with levels unaltered from a linear extrapolation of current budgets.
- **\$ ISS Ops (=JSC Mission Ops) - Transition - to \$ Exploration Mission Ops:** Consistent with assumption #3 (ample doses of skepticism and rigorous assessment must accompany any notion that funding from one program ending might become wholly available to fund another) ISS operations are equated to standing functions for JSC mission operations. These operations could morph into other mission operations in support of deep space exploration. Their level is left unaltered from a linear extrapolation of current budgets.
- **← ISS R&D, Crew & Cargo \$ thru 20xx →:** ISS R&D and transportation support (US commercial cargo, crew and currently Soyuz) are placed aside a transition of interest, "←Post ISS \$\$\$ Funds Available→", albeit uncertainty remains about actual funds availability even after the prior treatment of ISS operations.

For any projects placed below the dashed red/blue line there will also be:

- Ground operations at KSC; other (new) operations as required
- NASA personnel (civil service), government management of programs / projects and related expenses. (The model calculates these in historical proportion to their associated projects.)

This methodology allows a relatively clear view of the playing field, with most of the real NASA dollars for this life cycle analysis in an unobstructed view at the bottom of the field. (The real NASA dollars are these "procurement dollars" that can be moved among investments, developments and acquisitions.) This is consistent with the new set of assumptions that are near opposite of the usual assumptions applied in a reconnaissance of possible futures.

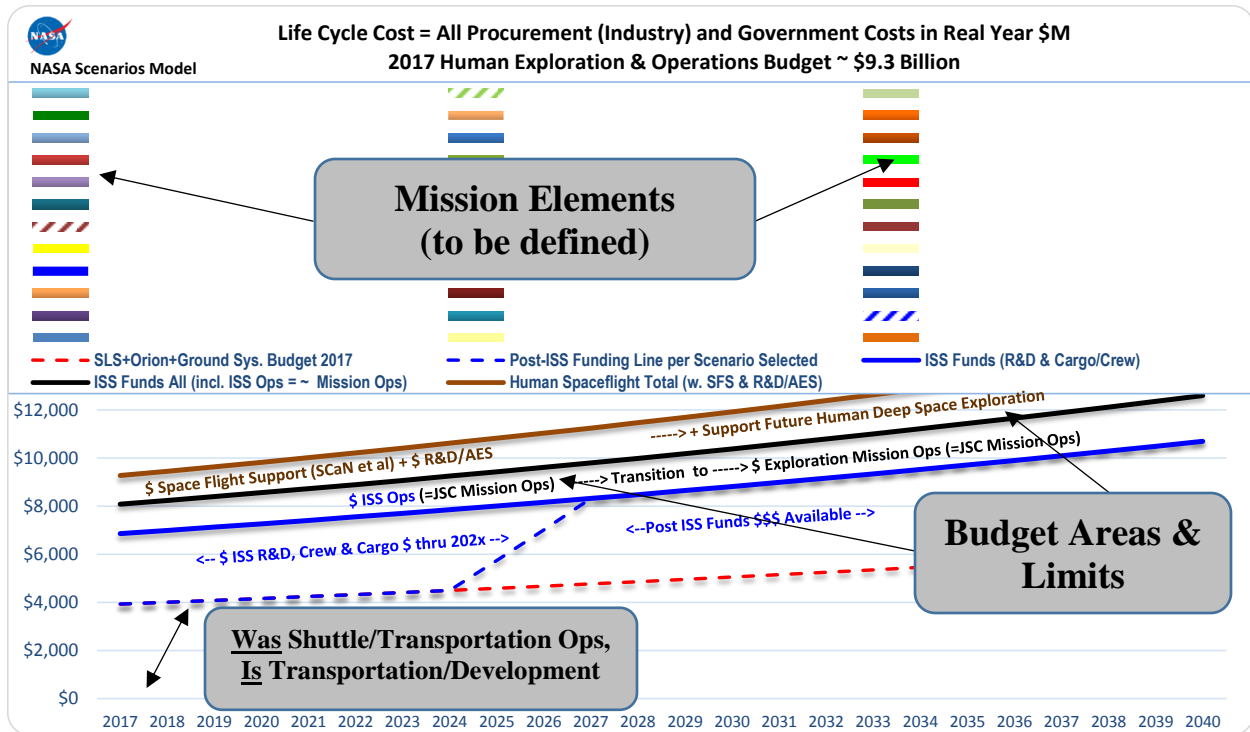


Figure 7. A blank NASA life cycle cost/budget scenario template. A complete view of the human space flight budget by categories helps show how any exploration elements life cycle costs might fit within a budget outlook.

IV. The Baseline Scenario

We begin with a Baseline Scenario in Figure 9. The scenario revolves around one launcher and one spacecraft currently in development and employing all the funds below the dashed (---) lines, the SLS and Orion. This includes associated ground systems (at Kennedy Space Center/KSC) for assembling, integrating, preparing and launching these systems, the government management (civil service) personnel, and related NASA costs. The up-front development costs represented from 2017 to 2021 are taken from public budget documents⁶⁰ and public NASA statements taking completion of these two systems developments to 2023 at a 70% confidence level.^{61,62} Essentially, the SLS and Orion and related annual development budgets continue about at current levels until 2023. These system developments are then complete after test flights (just as the first four Shuttle flights were part of development). EUS cost estimates are based on the on-going SLS experience, with public sources for similar size, type of stage and type of acquisition (cost-plus contracting) as sanity checks. The 2011 NASA Earth Departure Stage (EDS)⁶³ is the close cousin of today's EUS.

Beyond the near term to 2023, operational cost estimates for the recurring production of SLS and Orion hardware rely on historical Shuttle data. By way of example, we know the cost of Shuttle external tanks (ETs) across production ranges, the number of tanks produced per year (Figure 8). The core stage for the SLS is Shuttle ET derived, only much larger and much more complex (with main propulsion in the aft and payload integration forward). The SLS core stage cost estimate pegs off this Shuttle historical cost data. Costs estimates adjusted for this increased scale and complexity. Generating a 3-point estimate addresses the range of uncertainties. Adjustments for inflation and NASA accounting changes over time complete the cost estimate for the SLS core stage. The sub-system by sub-system (core stage, solid boosters, etc.) cost estimates together give the recurring total SLS fixed and variable costs shown in the Baseline Scenario Figure 9.

By way of sanity checking, note that the recurring SLS cost estimate is independent of the actual annual development cost. Yet the recurring yearly operational cost, here for 2 launches a year, comes in very close to the historical annual development budgets. This confirms the validity of the recurring estimate when considering the observation stated earlier in our methodology - "NASA projects and acquisitions historically favor stability, not roller coaster rides." In other words, a grossly simple recurring cost estimate stating that annual operations budgets would be about the same as annual development budgets would have arrived at the same basic numbers (without doing the actual analysis described previously).

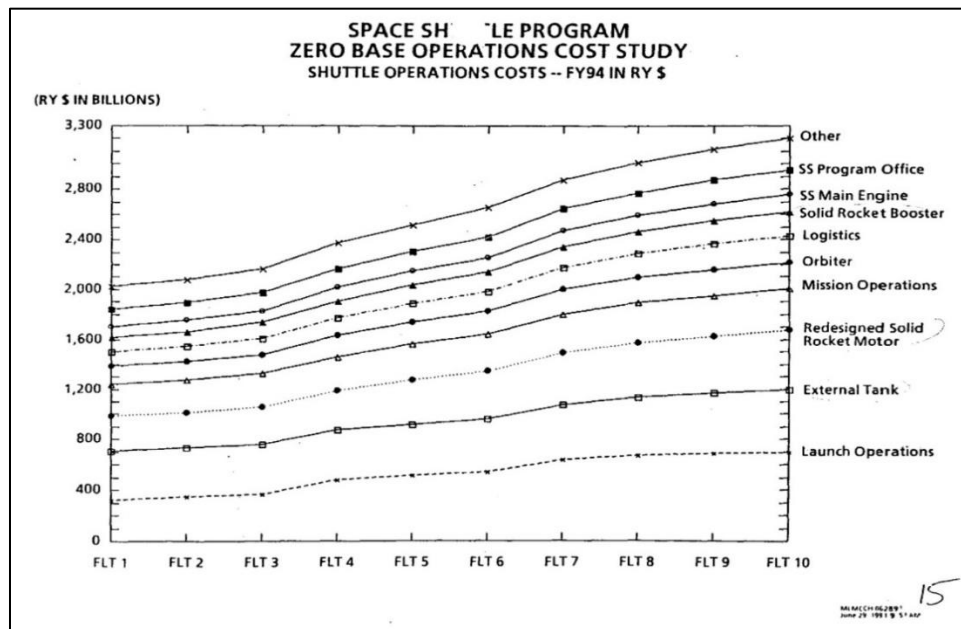


Figure 8. The Space Shuttle's "Zero Base" costs. This 1994 study showed how many Shuttle costs were relatively insensitive to flight rate. Flying once a year incurred about 80% of the costs of flying 5 times a year.⁶⁴ Interpretation requires caution, as the temptation is to believe that if fixed costs are high, then variable costs must be low, permitting an open-ended flight rate. This interpretation is incorrect. Each element of fixed costs also had low productivity, meaning that to further increase the flight rate significant additional capital expenses were required, negating the seeming advantage of the lower variable costs.

Consistent with public statements about the budget challenges for this program of record, the Baseline Scenario shows the annual costs at times exceeding the estimated annual budgets available. Uncertainties are not just about estimating recurring costs (the simple rule-of-thumb being to say annual development costs just go out to the future becoming operational annual costs). *The real difficulty is in estimating what outcome is achieved for a relatively easy to predict annual budget.* Cost estimating is merely difficult and tedious. Understanding cost estimates is challenging. The real work lies in estimating benefits, what you get for the costs, such as launches per year for a given budget.

Taking the Baseline Scenario forward, adding an Advanced Booster as in Figure 10, reveals how costs and ambitions increasing at a pace faster than budgets easily places a lien on 100% of any funding the end of the ISS might make available one day. This is just for the two launches per year, plus a replacement booster development in parallel, not payloads, not Mars or any mission in-space elements like habitation or landers. A Mars Design Reference Mission (DRM) that assumes a 130t payload (per launch) heavy lift vehicle by necessity may entail a replacement booster for the SLS. The estimate here assumes that such a tightly integrated system as the SLS, along with the historical costs data for the ongoing development, lends credence to the replacement boosters becoming a re-development of the SLS rather than just a tack on of a new plug-and-play booster replacing the solid rocket boosters (SRBs). To date the SLS is on target to be an \$18.5 billion dollar development, a sum of all budgets 2011-2023 (in 2017 dollars; nominally the total would be \$20.5 billion, for the 70t payload capability, excluding the exploration upper stage).^d

This begs the question of scenarios where the SLS remains at about the 105t payload capability long term or where its costs might decrease, our next scenarios.

^d All public budget data. Data sheet and documentation available upon request.

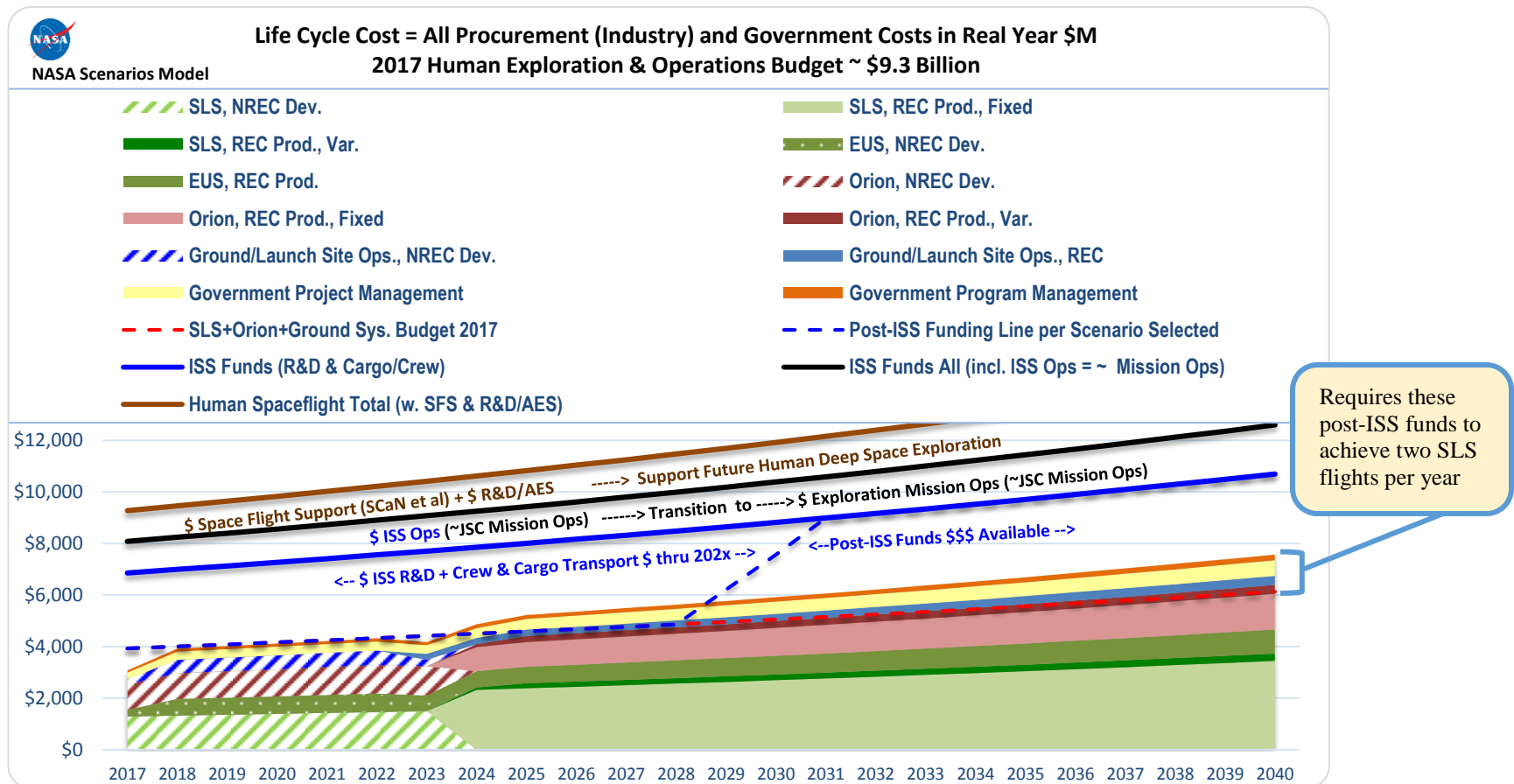


Figure 9. The Baseline Scenario, SLS / EUS and an Orion (every other launch). Productivity / benefit is = two launches of the SLS and one launch of Orion per year beginning in 2024. Payloads could be funded from post-ISS funds, in this scenario the white-space opening up after 2024 (←Post ISS Funds \$\$\$ Available→). If the ISS continues until 2028, the transition line moves to the right, with a need to lower the SLS / Orion flight rate below 2 a year through that date or find other cost reductions to remain below the dashed (---) available budget line.

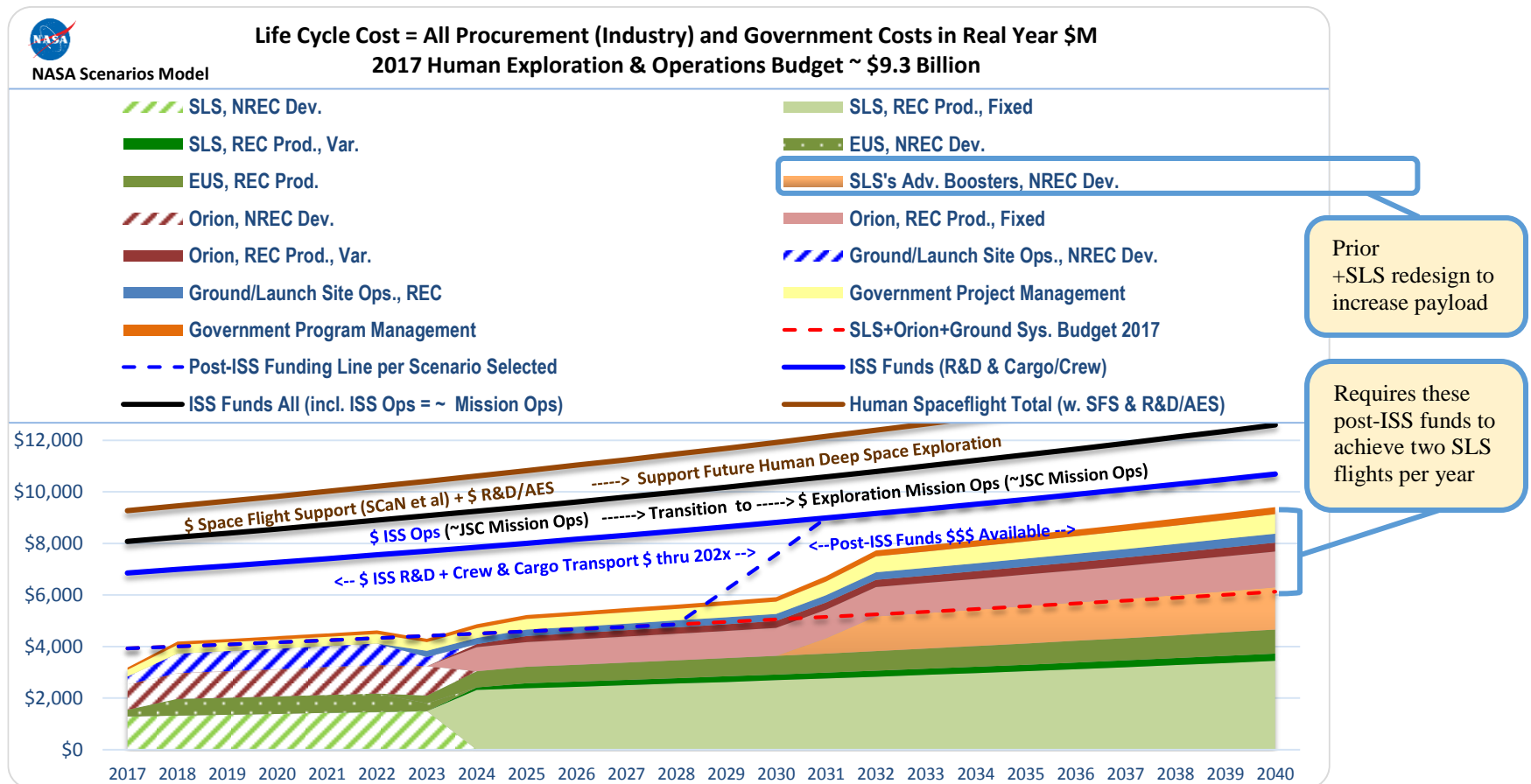


Figure 10. This is the same as the prior Baseline Scenario, except beginning an advanced / evolved booster development project after the end of the ISS to reach the congressionally mandated SLS 130t payload capability. This is also a capability required in the NASA Mars Design Reference Mission (DRM). The scale of the potential yearly cost for an advanced / evolved booster development, in parallel to ongoing operations of the SLS, to take the SLS to a 130t payload capability (to LEO) is put here on a par with the original SLS annual development costs. This is in consideration of the potential extent and scale of new advanced / evolved boosters⁶⁵, similarly on a par with the SLS experience to date. It's assumed the advanced / evolved booster is acquired with contractual approaches similar to past SLS approaches (partnerships, or partnerships and reusable advanced / evolved SLS boosters, are not considered here.)

V. Scenarios: SLS/Orion, Commercial Lunar Lander, EUS & Deep Space Spacecraft

After the baseline scenarios in Figure 9 and Figure 10, we can add commercial elements in steps as shown in Figure 12 (adding a commercial lunar lander), Figure 13 (changing the SLS upper stage, the EUS, to a commercial item), and Figure 14 (changing the deep space spacecraft to a commercial item).

This Figure 12 scenario is a hybrid that depends on properly estimating the costs to NASA for a lunar lander in a public private partnership / commercial approach. NASA acquires, or more properly said invests, in the development of a capability it later acquires on a recurring basis as a commercial service (see side-box below). Separate work describes the cost estimates for elements like this.⁶⁶ The lunar lander chosen for this scenario is the relatively large Altair concept, but smaller lunar landers like the Apollo Lunar Module (LM) result in similar looking life cycle costs. To vary things, the ISS continues through 2028. The lunar lander as a public private partnership is in keeping with the US commercial crew program, also a spacecraft that carries people. The lunar lander public private partnership estimate (Lander PPP) is an average of low and high commercial estimates to take into account uncertainties. Typically, such programs would have two providers, consistent with low / high cost estimates.

Unfortunately, the Figure 12 scenario runs into difficulties long term. It uses most all of the available post-ISS funding. This begs the question of what becomes of longer-term ambitions like Mars. The next step (Figure 13) hybridizes the scenario further, with the SLS EUS also a commercial item. This helps reduce costs significantly. This scenario is not out of the question. In a cost-plus contract, a contractor delivers hardware to KSC. The hardware switches hands at a certain milestone in the contract and becomes US government property. While other contractors in ground operations perform processes to get the hardware ready for launch, the element remains government property. A Shuttle stack involved Solid Rocket Motors from one contractor, an External Tank from another, Orbiter's from a company that eventually ceased to exist, absorbed into another, and engines from Rocketdyne that at one point had turbo-pumps from its competitor Pratt & Whitney. This begs the question of a commercial option for the SLS EUS. The notion the upper stage and core stage are too tightly integrated, justifying a cost-plus/sole source contract, is questionable by history. As with the Shuttle's multiple companies manufacturing major elements, three different contractors (Boeing, North American and Douglas) built the Saturn V's three stages – also a tightly integrated system. A revised acquisition approach for the EUS with an additional commercial partner is a topic worth assessment wholly consistent with multiple contractors providing hardware for a vehicle.

Figure 14 is the natural next step down this path of hybridizing an exploration system scenario, mixing cost-plus and commercial elements. Now the deep space spacecraft, Orion in the baseline scenario, is instead a commercial deep space spacecraft. The cost estimate for this builds off cost data to date for the US commercial crew partnerships. Figure 11 shows where a basic rough order of magnitude estimate might begin. The actual estimate used in the Figure 14 scenario for a commercial deep space spacecraft is further refined.

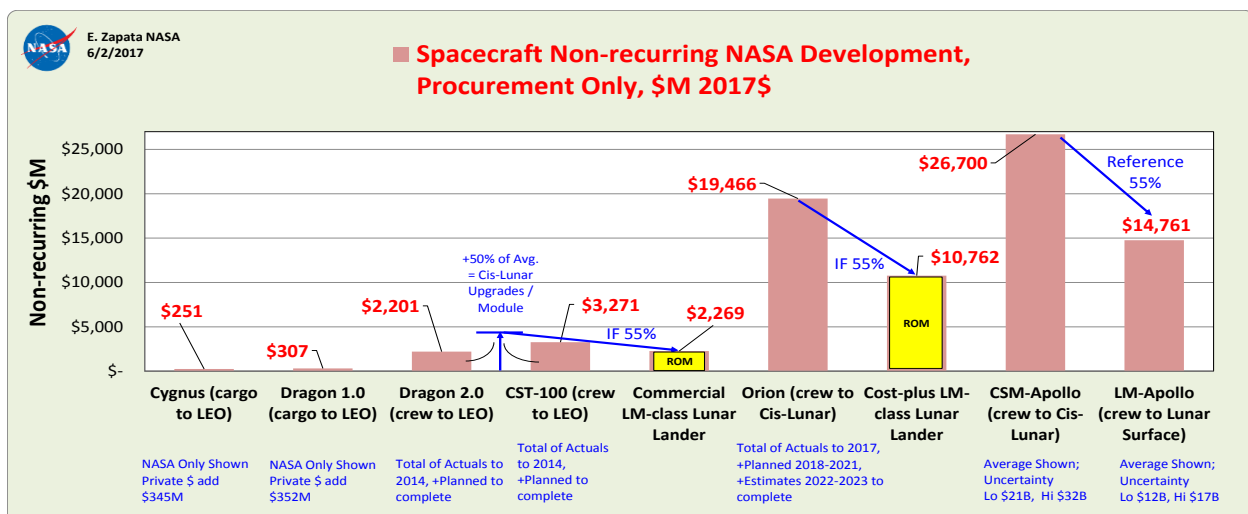


Figure 11. Assorted up-front spacecraft development costs. These are up-front development costs for the spacecraft only, not the associated launchers. There are contractual differences, with commercial spacecraft (CST-100, Cygnus, Dragon 1.0 and 2.0) up-front cost including the development of the required ground and mission capabilities, versus the cost-plus / traditional spacecraft acquisitions (Apollo, Orion) where the development of associated ground and mission capabilities is not included. There are also differences in capability (LEO, cis-Lunar, Lunar Surface).

This last scenario is especially promising, with the favorable characteristic of ample margin for error, margin for changes in direction, and the possibility of optimizing further to achieve significant milestones sooner rather than later – all white-space below the dashed (---) available budget lines. This is achievable even on declining purchasing power, as the public private partnership essentially stays ahead of the budget curve in an almost deflationary sense, the same basket of goods (the deep space spacecraft) costing significantly less in the future. This is also achievable without a resort to deviating from historical data, here reliant on the ongoing US commercial crew cost data.

Although beyond the scope of the work here, the scenario in Figure 13 has a subjective programmatic advantage, with the transfer of funds upon the re-direction of Orion likely circling right back to the same NASA centers and organizations that worked the Orion effort. A scenario where a relatively moderate disruption in contracting and funding, especially by location (NASA center or state), also allows for significant new possibilities is difficult to locate in any model. Understanding program fund flows to assess this factor of programmatic attractiveness, especially attractiveness to stakeholders outside NASA, is beyond the scope of the work here but worth future consideration and analysis.

Having hybridized the Baseline scenario gradually, life cycle cost scenario analysis can go still go further, explored ahead.

Why jump to a public private partnership / commercial lunar lander?

A recent Jet Propulsion Lab study estimated a Mars lander and Ascent Vehicle cost of \$44 billion⁶⁷ through the completion of a long duration surface stay.

Our independent cost estimate of the same type Mars lander in a cost-plus approach is \$36 billion for development (only). The rough consistency of these numbers reaffirms our methodology here.

Our estimates for large lunar landers (Altair-class) approach similar cost levels, a range of \$21-27 billion dollar developments.⁶⁸ But, rather than smear one or two billion dollars a year in cost-plus contracts in life cycle cost graphs, extending development out practically forever at these values, the scenarios we highlight include commercial lunar landers costing significantly less. This fits the scenario to explore, such as a lunar return, within shorter, relevant timelines.

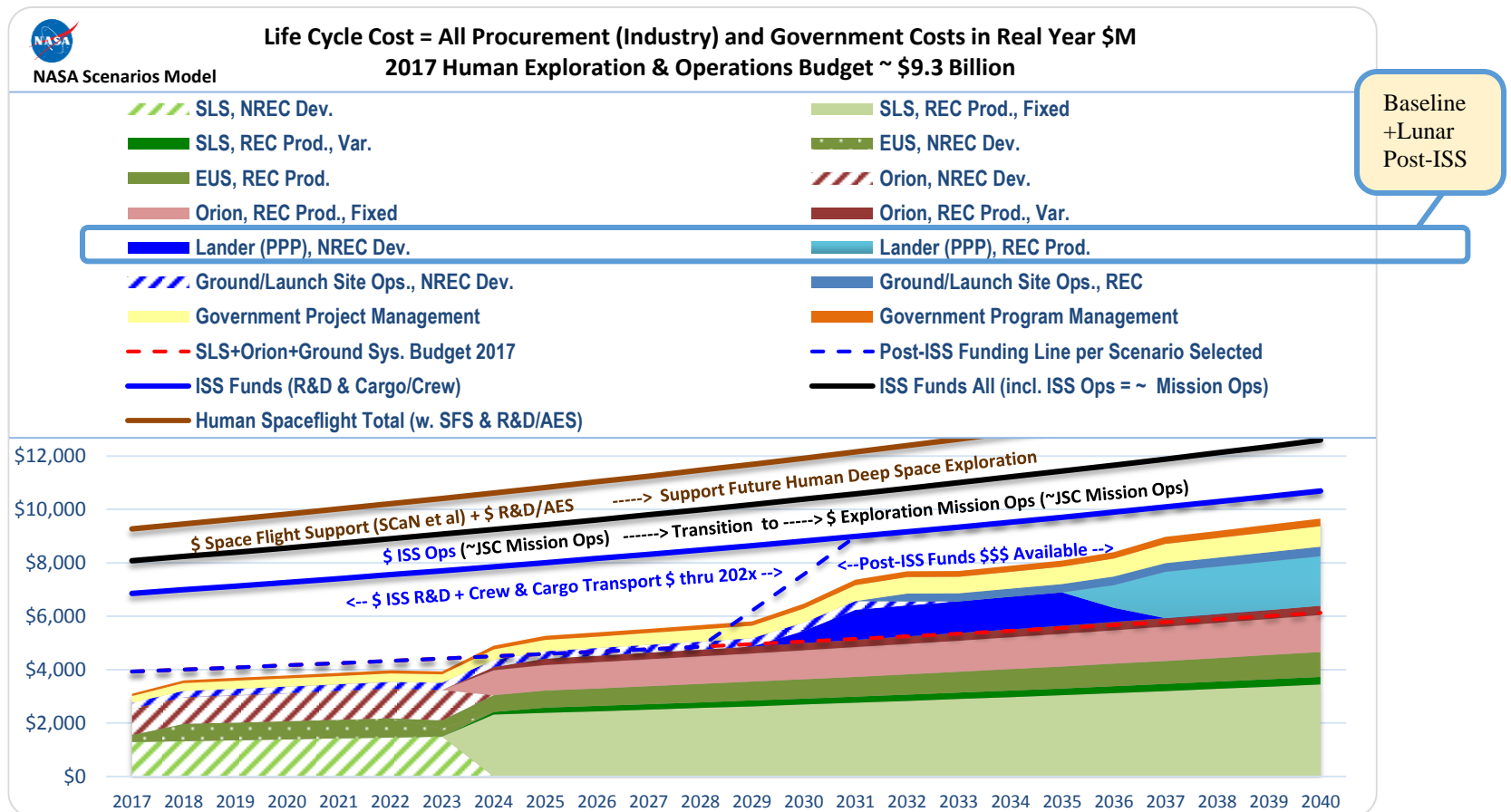


Figure 12. A Return to the Moon in 2037. In this scenario, an alternating SLS/Orion/lander tempo allows for a return to the Moon after completing a commercial lunar lander development. The nearer term SLS / EUS payload capability is adequate to achieve this type of scenario. Crewed lunar missions would occur once per year starting in 2037. As with previous scenarios, costs exceed budgets in the years before the end of the ISS indicating a need to reduce the flight rate before the end of ISS or find other cost reductions so these remain below the dashed (---) available budget lines.

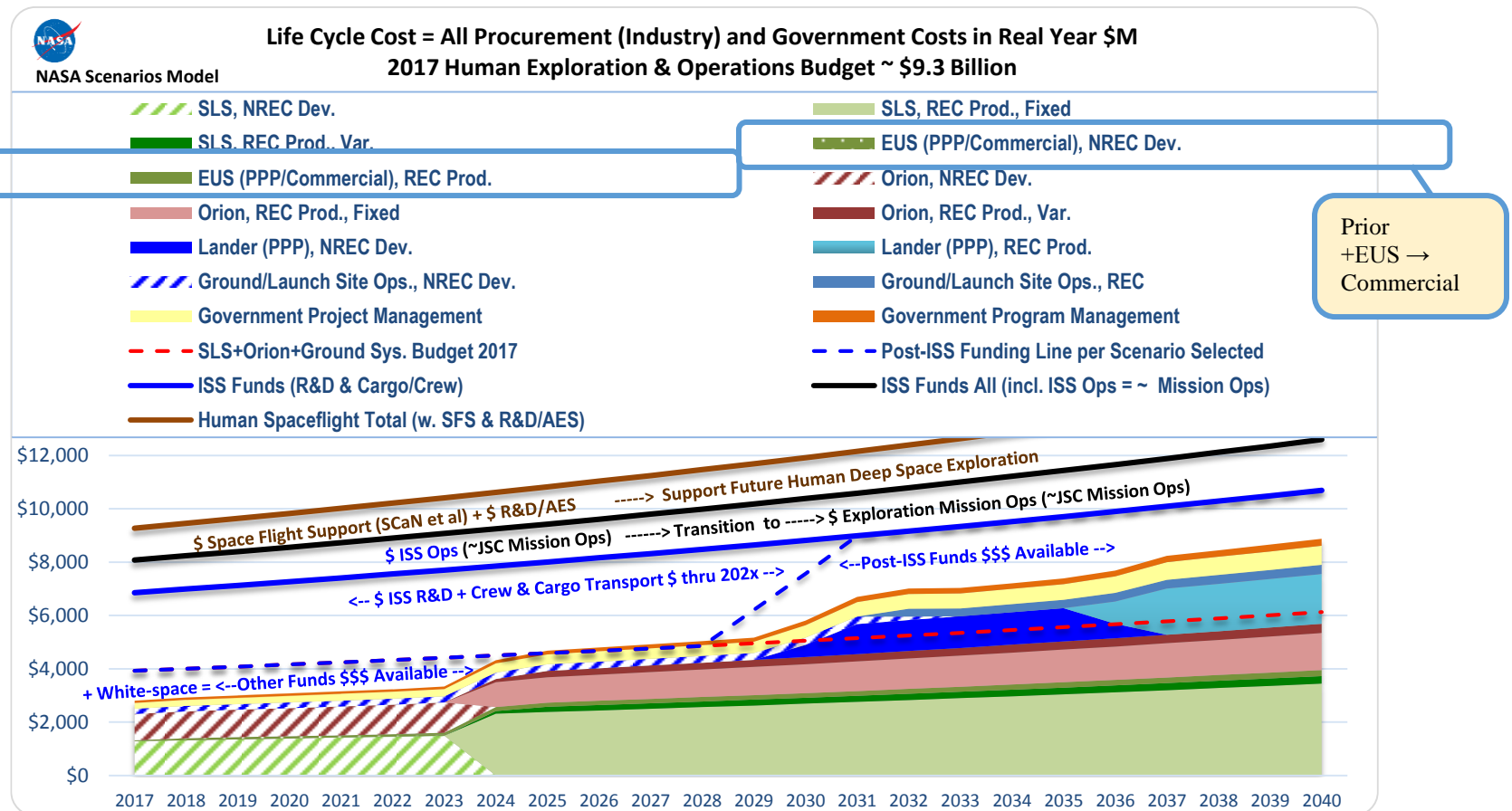
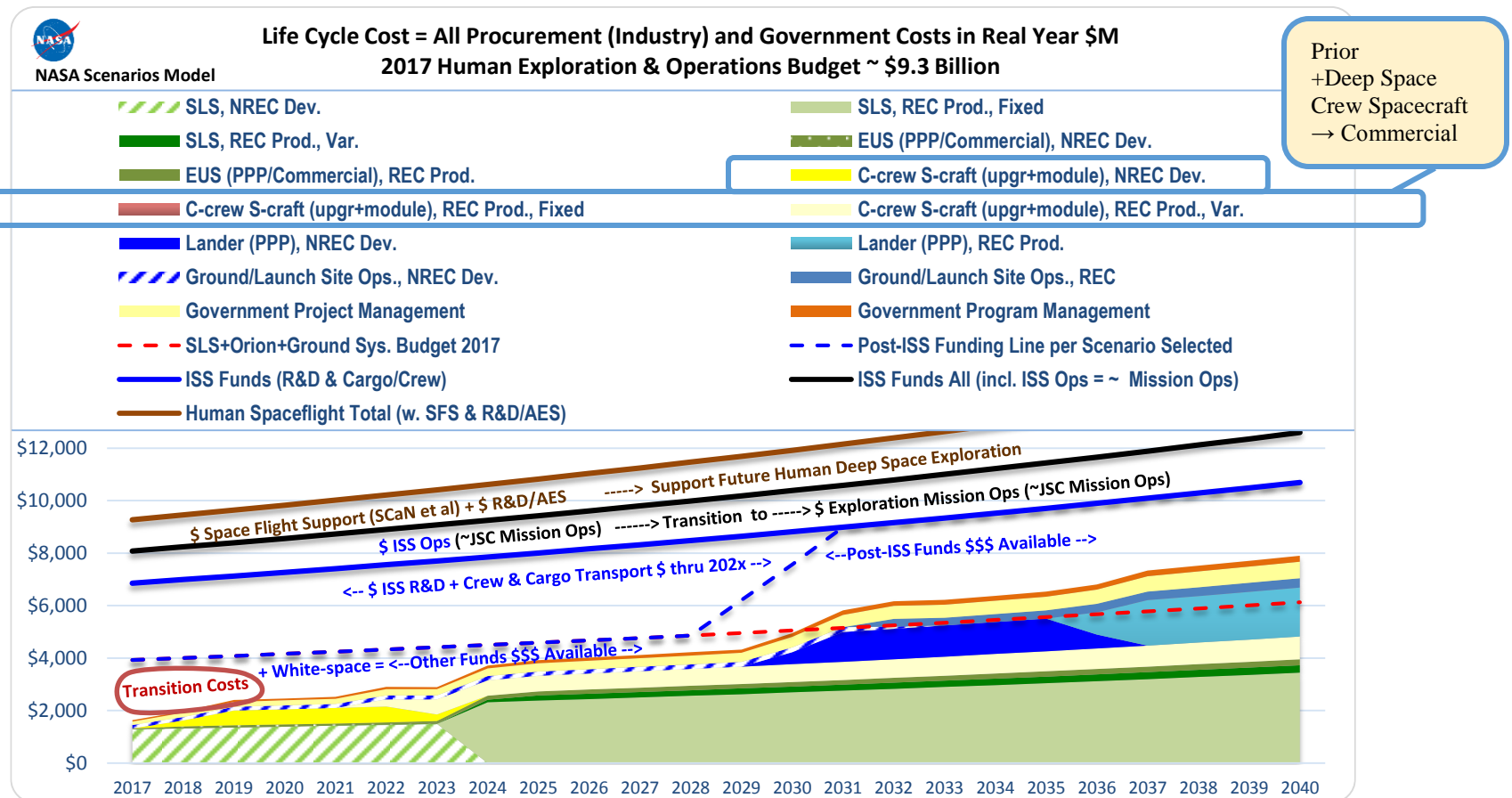


Figure 13. This is the same as the prior scenario, except the EUS is a public private partnership rather than a cost-plus/sole source contract. This leaves room to grow in the near term, assuming the same annual budget levels as would have been available for a cost-plus/sole-source effort. There is also some room to grow in the far term, the white-space unassigned after 2028 (←Post ISS Funds \$\$\$ Available→).



VI. Scenarios: Commercial Heavy Lift & Refueling

The cost reductions seen in public private partnerships and commercial launch service acquisition over traditional cost-plus and/or sole source contracting open the door to scenarios where NASA acquires heavy lift services commercially. There is no reason to draw a line at low Earth orbit beyond which all things must be cost-plus. Uncertainty in complex technology efforts justifies a cost-plus contract mechanism, payment for effort that is uncertain as to results. However, recent developments have added certainty to many space systems, justifying a look at commercial contract mechanisms. Other work has assessed opportunities for public private partnerships and commercial space systems beyond LEO – concluding, “Including these commercial options in NASA space exploration architectures, that assembly of many space systems for specific missions, could significantly improve two factors where NASA exploration programs face difficulties. Deep space systems as public private partnerships could significantly reduce the cumulative cost of deep space exploration elements while addressing the risk of irrelevance, as reduced costs equal outcomes that are sooner rather than forever a matter for another generation.”⁶⁹

Because commercial heavy lift may not approach the SLS 70t or future 105t payload capability, the commercial heavy lift scenarios explored here include in-space refueling.

The 2009 Augustine review of human space flight stated –

“Since it is very constraining to balance mission components to always partition equally between launches, this strongly favors a minimum heavy-lift capacity of roughly 50 mt that allows the flexibility to lift two “dry” exploration elements on a single launch.”

“All of the options would benefit from the development of in-space refueling, and the smaller rockets would benefit most of all. A potential government-guaranteed market to provide fuel in low-Earth orbit would create a strong stimulus to the commercial launch industry.”⁷⁰

The later 2014 NRC review of human space flight stated –

“At present, the crossover point at which an SLS-based approach would be more economical than an approach using smaller launch vehicles has yet to be determined.”⁷¹

A NASA team looked at propellant depot scenarios in 2011. The cost estimating approach for stages, tankers and the depot have since been refined. Changes in assumptions are minor (for example, there is no assumption of cost commonality in manufacturing between propulsion stages and depots in the work here, a more conservative assumption). Overall the new results confirm earlier findings that refueling scenarios are promising, with ample margin for error in cost estimation and for inevitable “unknown unknowns”.

Figure 16 shows an in-space refueling architecture used for lunar exploration where the SpaceX Falcon Heavy in development becomes NASA’s commercial heavy lift provider. The deep space spacecraft and lander are the same as in prior scenarios, also public private partnerships. The new element is the propellant depot scaled for filling from tankers rendezvousing in low Earth orbit such that enough propellant is available to support 1 lunar mission per year.

There are issues with the scenario. A transition to such an architecture would be a major undertaking, redirecting funds from two major NASA programs, SLS and Orion, and all associated projects like ground systems development. That “Transition Cost” is the white space at the start of the life cycle in Figure 16. Addressing details here is beyond the scope of this analysis, but the amount of “Transition Cost” in the scenario represents a realistic amount of funding at the front end for this case. Forward work could address what is inside the macro-level “Transition Cost”.

More importantly, the Falcon Heavy centric scenario suffers from dependence on one launch provider, a formula for disincentives and unforeseen, undesirable consequences. This issue is resolved by realizing that multiple heavy lift providers in the 50t payload range might exist in the near future. A Blue Origin New Glenn launch vehicle or a United Launch Alliance Vulcan are also possibilities well within the timeframe of this scenario. In addition, a distinction is required between acquiring propellant from multiple providers versus acquiring only one heavy lift provider delivering semi-dry space system elements. A segue to a scenario that is generic, with multiple providers, can look at the Falcon Heavy scenario as undesirable but still critical, as an existence proof that such costs per kg of propellant are achievable. The Falcon Heavy centric scenario is already conservative, increasing its advertised price in proportion to the prices seen in NASA contracts for the Falcon 9 (56% more than private sector pricing⁷²), even for propellant that is low mission critical (relatively easily replaced). Even so, with amortizing of the propellant depot operations, eventual

replacement depots, additional depot operations apart from mission operations, the vehicle and tankers, and accounting for propellant losses (boil-off, etc.) the cost per kg comes in at \$5,200/kg for this scenario.

Figure 16 shows an improved scenario with multiple launch providers. Conservatively, the life cycle cost profile goes up slightly, counter-intuitive given the increased competition. However, this is consistent with costs increasing as more and relatively smaller vehicles provide propellant to the depot at a higher cost per kg. Eventually the acquisition model might procure propellant at the depot, not launchers and tankers (a step beyond even the current paradigm where there is no payment distinction between an Atlas launcher and the Cygnus cargo spacecraft in a total cargo delivery price to NASA). Notably the launcher/tankers and landers recurring costs are the two layers that dominate the scenario, followed behind by the layer of cost for the commercial deep space spacecraft.

When last studied in 2011 these propellant depot scenarios had some assumptions that have proved conservative over time. NASA would have paid for up-front commercial heavy lift development at the time for Falcon Heavy and Delta IV. It is clear now both of these developments and others will require little to no up-front NASA investment. Blue Origin's New Glenn vehicle at 45t of payload to LEO adds a 3rd contender not considered in 2011. Future analysis could resurrect older assumptions, to understand the scenarios further, such as commonality between stages and the propellant depot, a way of sustaining the capability for the depot "Replacements". Figure 15 shows the stage with this commonality assumption. Future work will look at more variations on this theme, as ultimately the requirement is for propellant loaded into semi-dry exploration elements, especially an Earth departure stage, not for a depot intermediary.

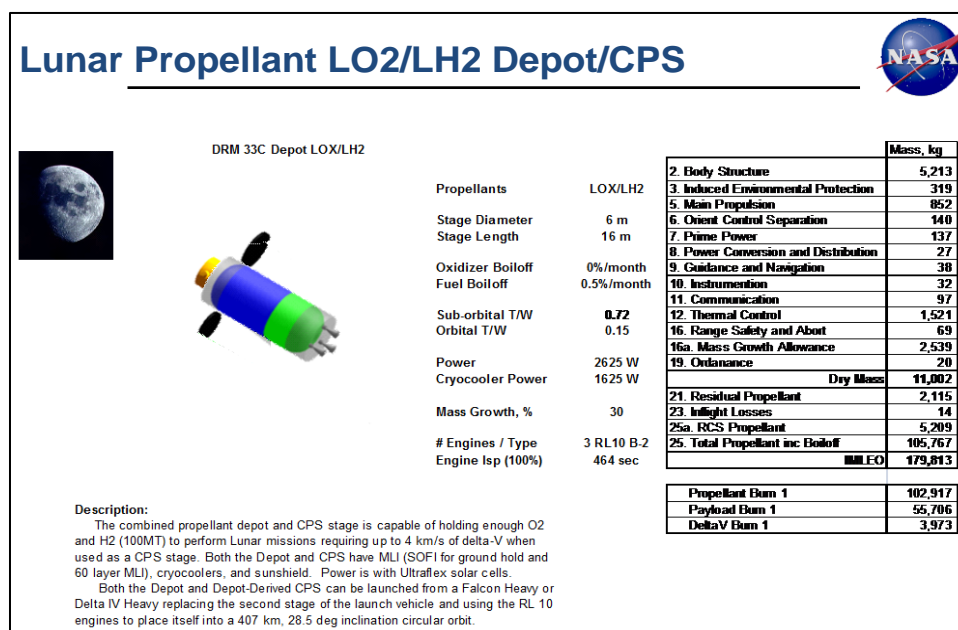


Figure 15. The combined propellant depot and chemical propulsion stage is capable of holding enough O2 and H2 (100MT) to perform lunar missions requiring up to 4km/s of delta-v when used as a propulsion stage. From the 2011 NASA Propellant Depot Study.

On that note, actuarial flow of funds requires significant attention. NASA as investor might deal separately and in differing degrees with the propellant depot versus the launchers and tankers for propellant. Once operational, ideally NASA might pay for propellant at an interface in-space as a material commodity under some sort of servicing agreement that is "services for servicing the departure stage". Here the owner of the propellant depot would contract for launchers and tankers, with NASA perhaps entirely if not mostly uninvolved in that process. This is completely analogous to how NASA contracts with a partner, not the partner's suppliers, just moving the outcome a step closer to the real goal – a serviced departure stage ready to leave Earth orbit. Alternately, contracting the launcher for the semi-dry exploration elements would remain the same as NASA currently contracts for commercial launch services for ISS cargo, ISS crew and other launches through the NASA Launch Services Program (LSP) at KSC. The incentive structure behind each element in these scenarios is a matter worth future assessment.

Having moved away from scenarios that depend on ISS funding, the next question is how scenarios might build on ISS, especially for going beyond the Moon.

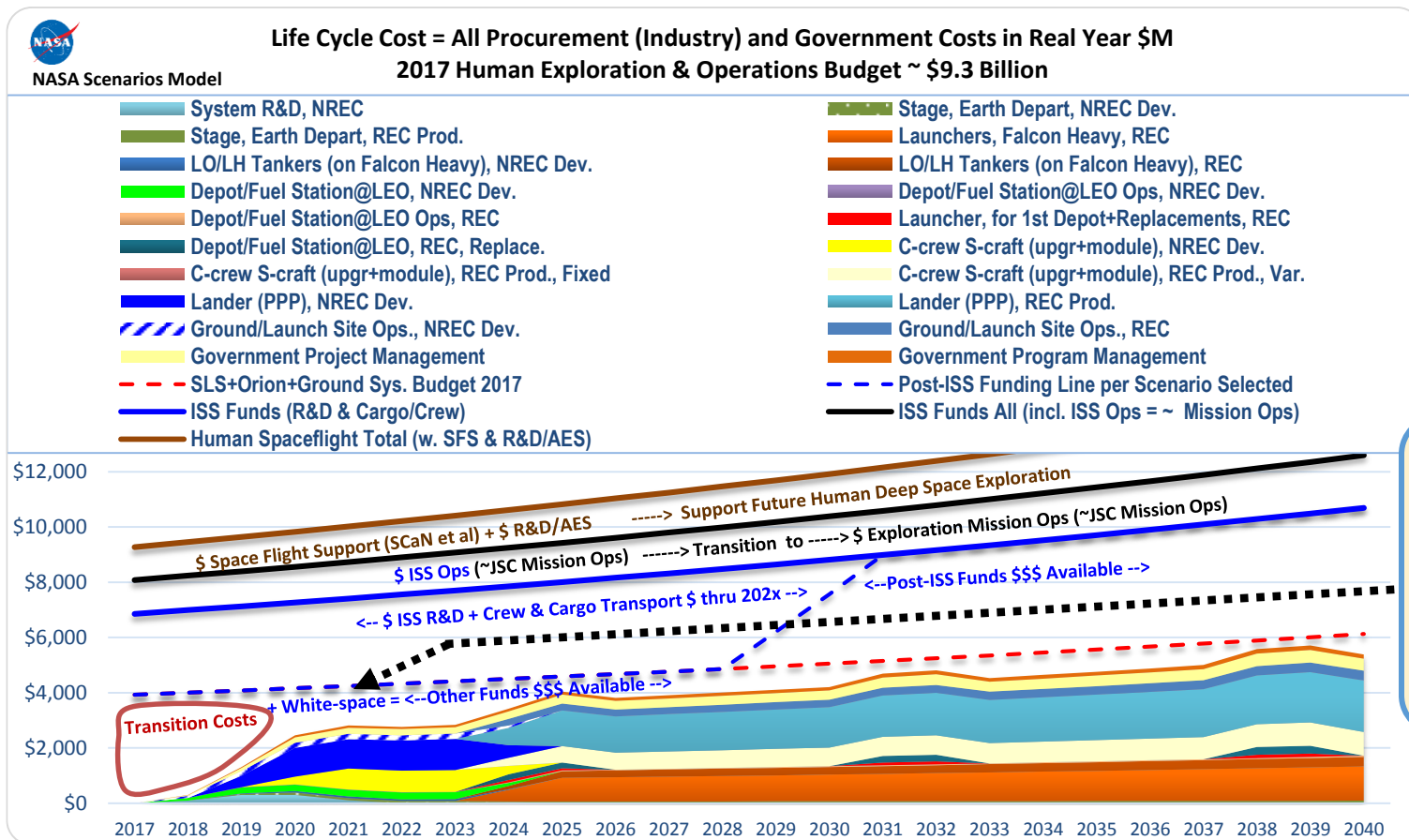


Figure 16. A return to the Moon scenario using commercial / public private partnerships, a propellant depot, and reliant on the SpaceX Falcon Heavy launch vehicle. Productivity / benefit is = a lunar landing in 2025 and an operational capability to repeat these lunar landing at a pace of one a year.

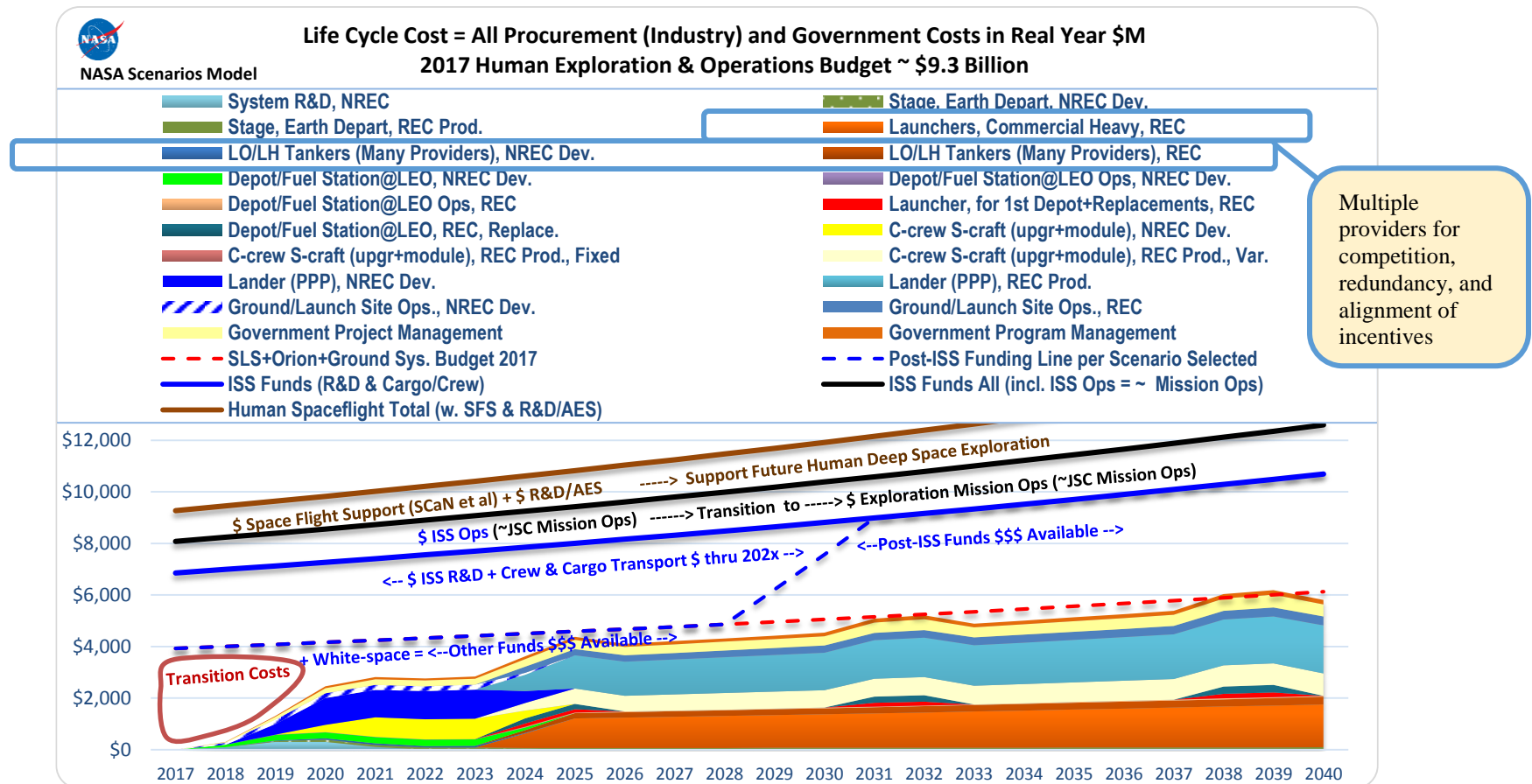


Figure 17. A return to the Moon scenario using commercial / public private partnerships, a propellant depot, and multiple competing commercial launch and propellant providers, of which at least one is in the 50t to LEO payload range. Propellant available at the depot is paid for by a customer (NASA) at ~ \$7,000 per kg (in 2017 \$). The productivity / benefit is a lunar landing in 2025 and an operational capability to repeat these lunar landing at a pace of one a year. Different business case models might apply, with NASA at one extreme collaborating with individual elements in different business arrangements, launchers, propellant tankers (or both), propellant at the depot, or for development and operation of the depot, versus another extreme where NASA pays for propellant at the very end, when a stage arrives for refueling services.

VII. Scenarios: Journey to Mars

The planning notion of a “capability” driven framework appears in an entirely new light with the realization that if deep space scientific and exploration objectives are the end goal, then deep space elements like ships and landers are a means to that end. From this view, launch systems to space and propulsion in-space are support systems, like infrastructure, so the deep space elements like ships and landers can leave on their way. Very different support systems can achieve nearly identical ends, the ships leaving the vicinity of Earth-space. This perspective is not new, as the NASA Mars DRM study in 2010 looked at SLS-like heavy lift options for a nuclear powered fleet, for chemical propulsion fleets (with in-space propellant transfer), and for commercially delivered propellant in complement to the SLS-like heavy lift launcher (then called Ares V). Although the end elements leaving Earth-space varied somewhat, from 800 to 1,200t of mass at LEO to be sent along to Mars, there are enough similarities to bound life cycle cost scenarios.

Heavy lift DRM SLS-like options required 7, 11 or 4 SLS scale heavy lift vehicles, the lower number with 4 launches being an option including commercial refueling of the departure stages. The SLS-scale vehicle launched the departure stages and deep space systems to LEO. Figure 18 shows this option.

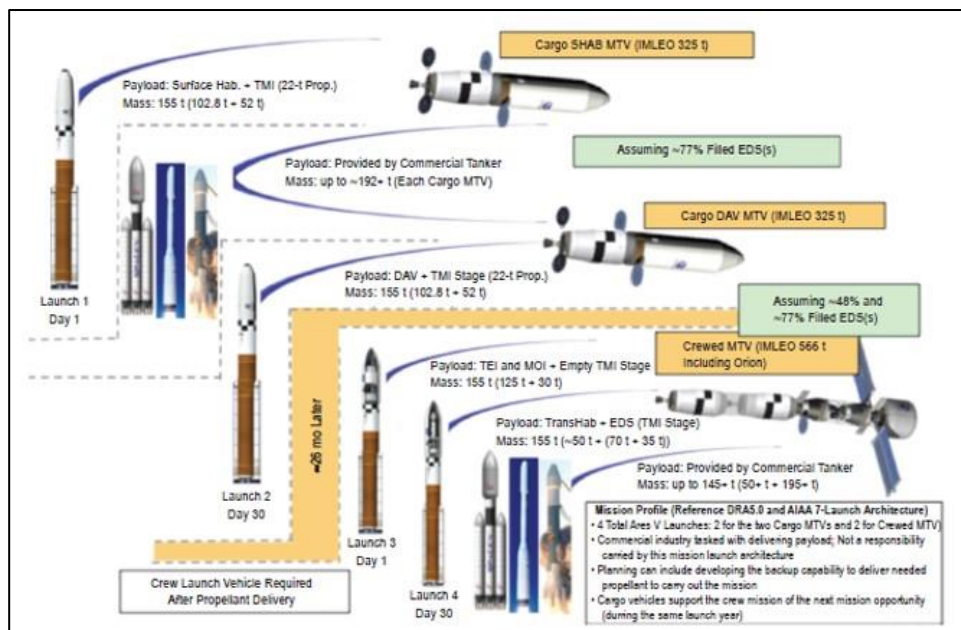


Figure 18. A “Commercially delivered propellant option (EDS tanker derivative)” from the 2010 NASA review of its Mars design reference mission (DRM).

To gain insight into potential life cycle scenarios for exploring Mars we again separate the three elements of capability, propellant and payloads in a way similar to the 2010 review. The real “reference” in the design of a Mars mission is certain items in space, of certain masses, sent on their way to Mars. How the items arrived in space and what pushes these items out to Mars are all about “how”, the means to an end. The task is sending the ships along to accomplish scientific objectives, to explore strange new worlds. Nonetheless, everything – transportation to space, transportation to leave Earth-space, and the elements (ships, etc.) - all use funding from the same bucket of money, the NASA human space flight budget.

To simplify, with the items and masses leaving Earth-space in the NASA Mars DRM as a constant, we can look at life cycle cost scenarios around propellant and mass capabilities, without having to address specific payloads, manifests or co-manifests. The degree to which a scenario (1) allows for “white-space”, available funding, (2) is productive, a capability for more or fewer missions, while (3) remaining below assumed budget lines, are three criteria against which apples-to-apples normalized scenarios can be compared. The normalizing is against the NASA Mars DRM payloads, masses and items to send from Earth-space to Mars-space *AND* having to remain within likely budgets.

A potential method for understanding the life cycle cost of Mars exploration scenarios begins by taking the NASA Mars reference mission, trying to remain within budget limits, and letting the frequency of Mars missions be an output. In other words, assuming stakeholder and advocate patience (albeit a poor assumption), squeezing almost any

architecture under a budget scenario is possible. What changes is the frequency of completed missions to Mars composed of some number of supporting launches and emplaced capabilities. In a long-term view, individual launches are not missions, *completed journeys of crew to and from Mars are missions*.

Figure 20 returns to the baseline scenario, placed in the context of the Mars reference missions. In this scenario, like the ones that follow, a certain quantity of mass and capability arises from the supporting launcher and systems, in this case the SLS and Orion. Although the 2010 Mars DRMs had a higher tempo, less time between launches of the heavy lift vehicles, it's still notionally possible to think about the 800 to 1,200t of mass to be sent along in those reference missions versus the capability of any specific systems squeezed (approximately) under a budget line over time. Different specific systems form different scenarios and an output is what funding is left over (if any), and what capability in terms of propellant and masses is emplaced in the Earth-space vicinity. In the case of the baseline scenario about 1,000t are emplaced every 5 years some of which are crewed spacecraft and other parts of which are propellant and hardware mass that will leave Earth's vicinity. Any Mars mission elements like habitation (a ship, a "gateway" etc.), it's propulsion, or eventually landers would come from the "←Post-ISS Funds \$\$\$ Available→."

Note that if we define a Mars mission as a *complete journey of crew to and from Mars* every X or so SLS launches (for example ten over 5 years) then we have indirectly set the funding limit for all the Mars element hardware – it's the X years worth of post-ISS funding in the diagram. If the Mars elements cost more, say 8 years worth of post-ISS funding, then a mismatch starts to occur with the supporting launch systems tempo, and Mars elements set the tempo.

The total payload funding for a mission is that total available for payloads in any timeframe set by the supporting transportation required for that mission over the same timeframe.

Figure 21 takes the pendulum a full swing in the other direction, where the goal is to get full stages in space and a certain amount of mass for the Mars elements. Using the propellant depot approach now means that every 5 years (a time slice just like the baseline scenario) there will have been 800t of propellant at LEO, usable at a rate of 200t a year, and about 250t of other hardware mass for a total of 1,000t – similar to the baseline scenario. What is different is the opening of significant white-space, large amounts of funding available before the end of the ISS that can be used for more Mars mission elements. This is so even after ample transition costs.

Figure 22 looks at an in-between scenario, combining elements of the baseline and a depot. Swinging the pendulum full sway in both directions (Figure 20 and Figure 21) begs the question of what things might look like somewhere in the middle. The 2010 NASA DRM (Figure 18) identified a case using 4 SLS-scale heavy lift launches with commercial propellant refueling of the departure stages. Tempo issues arise, for example a crew spacecraft that only gets used once every 4 years or so. Commonality with a commercial spacecraft for LEO / ISS use could get around this issue, just as occurred previously with the hybrid scenario in Figure 14.

Lastly, Figure 23 shows how a scenario at one extreme, a propellant depot architecture for lunar missions, can segue into Mars exploration. This is the case with other refueling architectures (Figure 21) – propellant doesn't really care what it's used for, and small depots and departure stages can lead to larger one's as an off-ramp whenever there is the white-space of other available funding. Similarly, the funding isn't assigned or necessary to a previous step, leaving space for new options such as private space stations.

Locating the intersection between possible business plans for private habitable space stations and NASA needs for habitation for deep space ship preparations (servicing, assembly, checkout, etc.) could vastly change the cost outlook of these. NASA would be one of many customers for an item produced at higher volume, not the only buyer. Similarly, development costs amortize over public and private users, lowering up-front costs to NASA. By relation, this means leveraging private investment, avoiding a situation where in-space habitation development is 100% funded by NASA.

Other variations on all these Mars scenarios are similar to those shown previously, addressing the EUS or deep space spacecraft as public private partnerships and commercial items on a recurring basis.

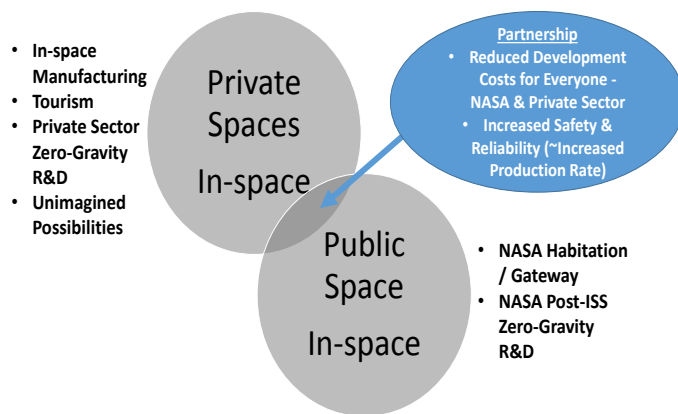


Figure 19. The benefit of locating the intersection of private spaces in-space and NASA (public) spaces in-space.

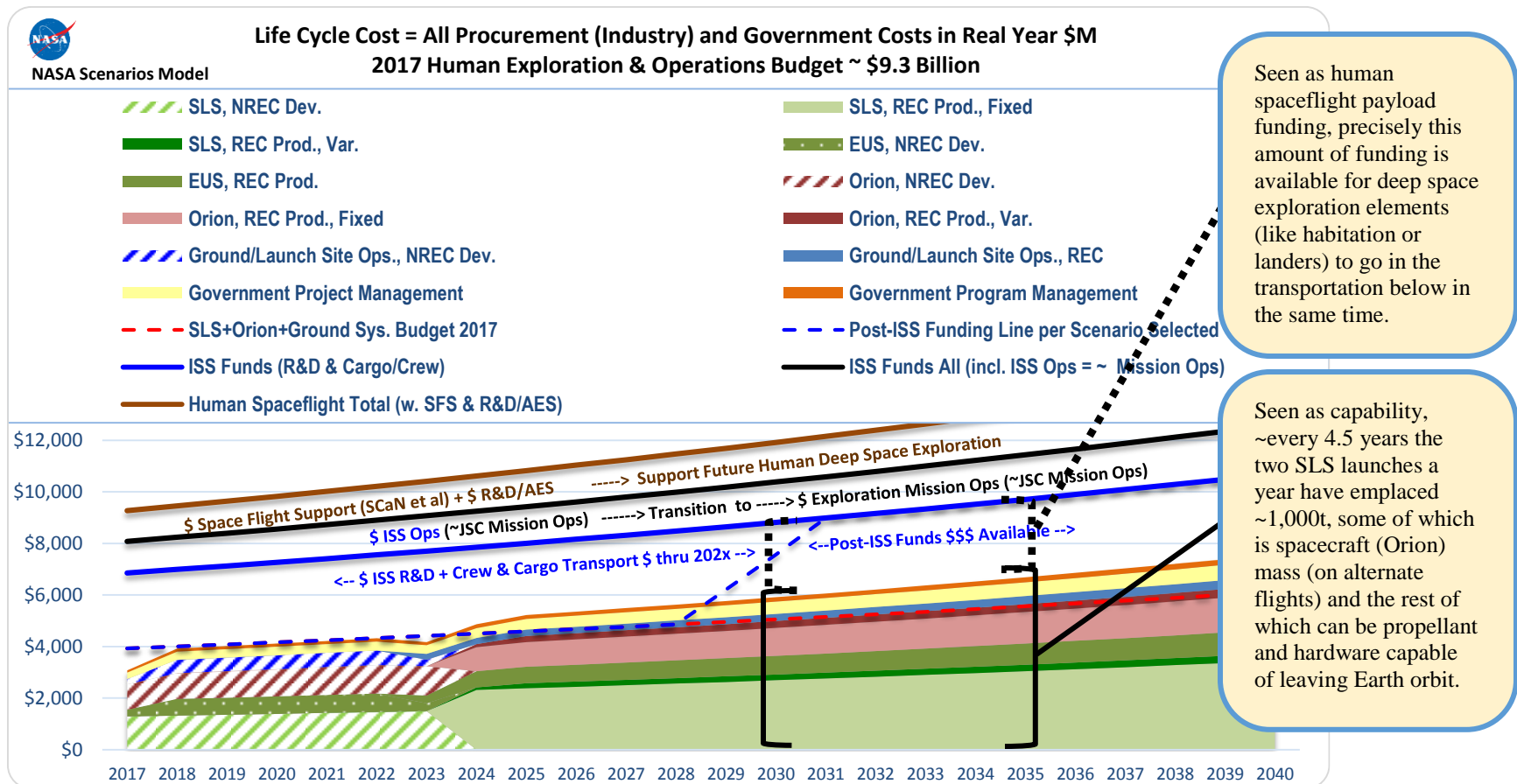
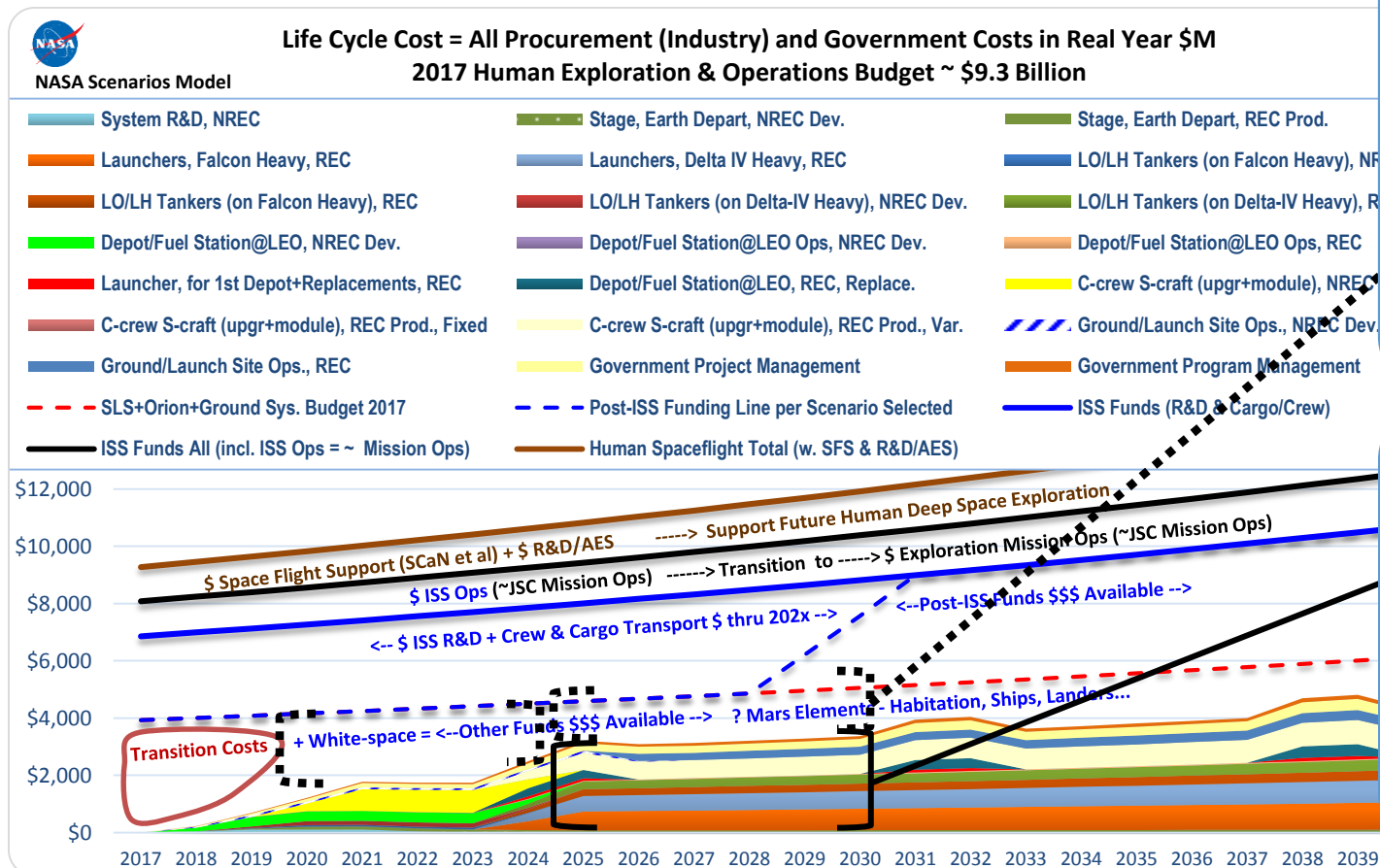


Figure 20. The baseline scenario seen as a capability for deep space exploration. The connection between any transportation capability and payloads as specific exploration elements (for example, habitation or landers) is apparent when looking at the whole as tonnage emplaced over any time by any supporting transportation system. The means, the supporting transportation system, and the ends, exploration elements leaving for deep space are by necessity fiscally linked. This scenario emplaces ~1,000t (metric tons) into low Earth orbit every 4.5 years, some of which is crew spacecraft, in this case Orion (4.5 times).

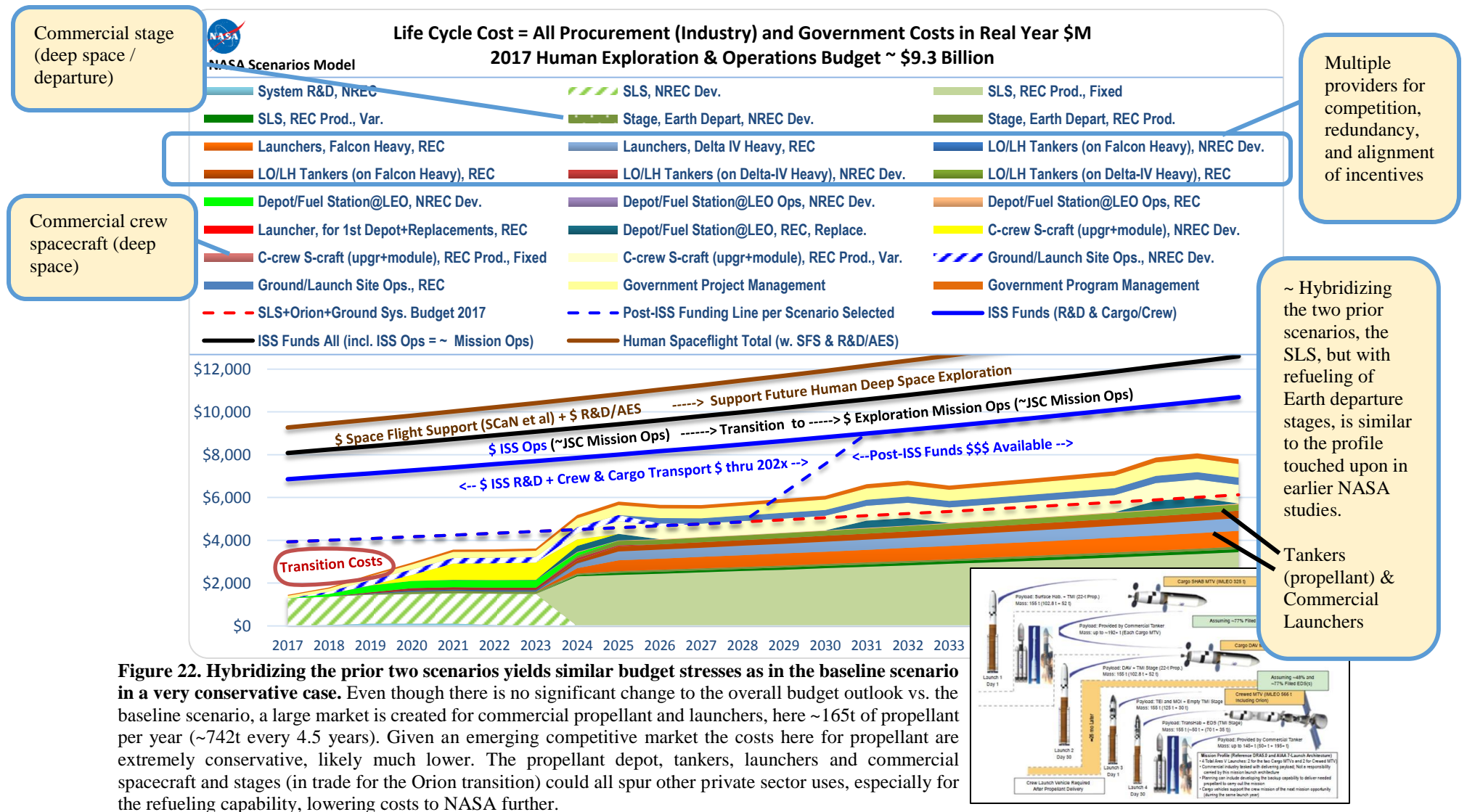


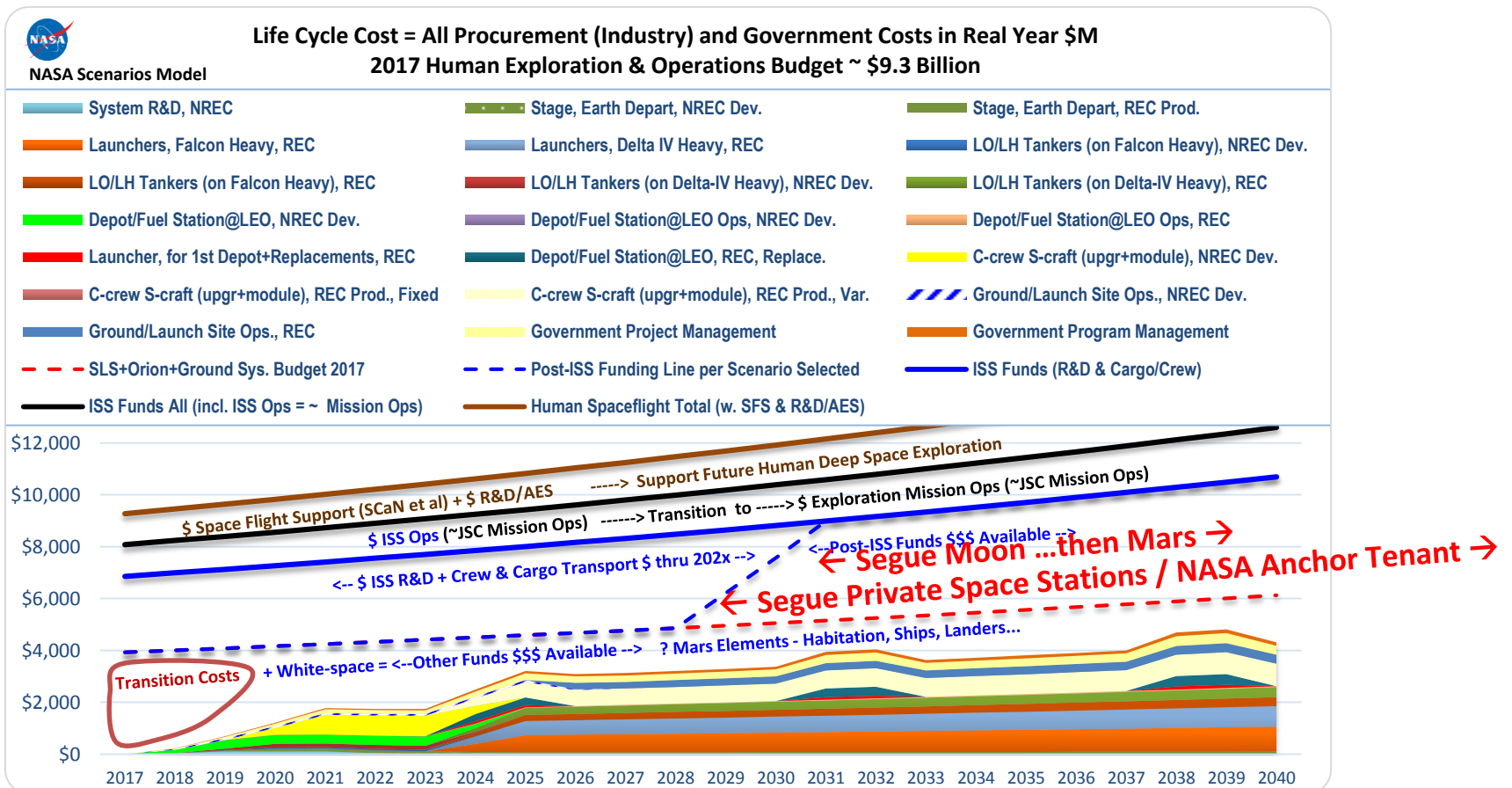
Seen as payload funding, precisely this amount of funding is available for deep space exploration elements (like habitation or landers) to go in the transportation below in the same time.

Funding is also available for this before this time.

Seen as capability, ~ every 4.5 years a mixed launch fleet has emplaced ~ 1,037t into low Earth orbit, of which 750t are propellant, some of which is spacecraft (commercial), and the rest of which can be propellant and hardware capable of leaving Earth orbit.

Figure 21. Deep space exploration as a combination of refueling and commercial launcher capabilities. The connection between any transportation capability and payloads as specific exploration elements (for example, habitation or landers) is apparent when looking at the whole as tonnage emplaced over any time by any supporting transportation system. The means, the supporting transportation system, and the ends, exploration elements leaving for deep space are by necessity fiscally linked. This scenario also emplaces a little over ~1,000t (metric tons) into low Earth orbit every 4.5 years, some of which is crew spacecraft, in this case commercial (4.5 times), and 750t of which is propellant and stages usable for going beyond low Earth orbit.





VIII. A Review of the Scenarios

Observing that certain scenarios say “no” is not new, that exploration is not really possible unless budgets increase, funds get moved around, and future operating costs drop. Finding alternate scenarios that say “yes”, sooner rather than later, is new – NASA space exploration is possible without any of the usual optimistic assumptions. There are sufficient relatively certain cost elements in NASA space flight and exploration to offer valuable insights into what’s ahead if these elements are combined with budget trends and an understanding of specific fund lines (putting aside items like Space Flight Support and Mission Operations).

Albeit, the scenarios that say “yes” have new difficulties, especially scenarios that transform more elements of the baseline scenario versus fewer. Scenarios that take smaller steps appear promising as these would appear to get around the difficulty of expecting too abrupt a transformation in NASA’s portfolio.

Two extremes bound the scenarios. At one extreme, favoring stability, relatively linear extrapolations of current events (Figure 9, Figure 10, Figure 20 and partly Figure 12) mean NASA ambitions must stretch and squeeze across extended timelines to fit outcomes and accomplishments within constrained budgets, a condition that carries the risk of increasing irrelevance. That is, the longer it takes to achieve an outcome the more easily and likely it is for a plan to be overcome by events.

At the other extreme (Figure 16, Figure 17 and Figure 21), favoring dynamic changes across most of human space flight to un-link planning from the end of the ISS, exploration can happen sooner rather than later. This requires significant shifts away from *development / acquisition* and toward *investment / services*. Here NASA must rebalance its portfolio in a way not seen historically.

Between these bounds, there are hybrid scenarios (Figure 13, Figure 14 and Figure 22). The sampling here is not intended to be complete – there are many other combinations of projects that avoid extremes. All move toward public private partnerships in one of more exploration elements, but not all. It could be said that the promising hybrid scenarios just slow down the transition from the linear extrapolations to the more dynamic scenarios, taking slower steps down the path of transforming NASA’s space flight portfolio.

Some scenarios, by virtue of their cost outlook, must inevitably link to plans for the end-date of the ISS (Figure 20, Figure 22) with an assumption all the funding there becomes available at the same time, to have any possibility of achieving exploration outcomes. Nonetheless, there are cases where no link is required immediately (Figure 21), architectures that can move significant budget resources toward in-space exploration elements (not transportation) before the end of life of ISS.

IX. Conclusions and Recommendations

“Implementable in the near term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth”

-NASA’s Journey to Mars, Pioneering Next Steps in Space Exploration

Different stakeholders might adopt any of the scenarios analyzed here for purposes of advocacy, or call all of them impractical, infeasible. Reviews since Augustine (2009) to the NRC (2012, 2014) and others all concluded only scenarios that increase the NASA budget significantly, or at least kept pace with inflation, reprioritized funds liberally, and dropped future exploration operating costs, among other optimistic assumptions, had any chance of achieving *any* deep space exploration. Even so, in these previous reviews exploration outcomes like humans on Mars remained more than a generation away.

The scenarios analyzed here avoided the usual generous affordability considerations - optimistic assumptions about budget increases, budget transfers and annual project costs that drop once operating, assumptions rarely observed in the real world. A critique may be that optimism about the ability to change projects inside NASA’s space exploration and operations portfolio (and their acquisition/investment methods) has merely replaced the prior set of optimistic assumptions – a magic trick, distracting with one hand what happened in the other. It is worth comparing optimistic assumptions and the outcomes that arise. Budgetary optimism and the other usual suspects not observed in the real world are still not enough to achieve exploration outcomes sooner rather than later. In the scenarios analyzed here, there are fewer optimistic assumptions, primarily transforming project lines consistent with real world NASA experience in partnerships significantly improving affordability. As importantly, here exploration outcomes occur much sooner rather than later.

In addition, an assumption about the capacity to change the NASA exploration and operations portfolio is plausible; it’s inside the current budgetary reality, while clinging to the usual assumptions about more funding for more outcomes does not lend itself to long term planning. A side effect of clinging to the assumption that much more

budget is required to do much more is that to the degree this does not become reality it creates the very uncertainty used to justify a lack of long term planning, a lack of reconnaissance of long-term scenarios.

In conclusion:

1. Long-term life cycle cost analysis for diverse NASA human space exploration scenarios is possible, practical and useful

Practical, useful life cycle cost analysis of NASA space exploration scenarios is possible, even with all the long-term uncertainties involved. Valuable insights arise when comparing a variety of possible directions in NASA space exploration relative to each other. This is especially so when scenarios are married to a budget context informed by history, not just about budget limitations, but about budget categories, functions and behavior.

Many certain enough elements combined with relatively predictable (historical) budgetary outlooks provide certainty about the difficulties or opportunities ahead. It's not critical to address space exploration taxi's, Mars landers, or a surface habitat (yet) to understand if there is likely little vs. ample margin of funding for these after putting the relatively well understood supporting systems in context. Further, in the spirit of planning for what is expected, but hoping for better, constantly refining our understanding of possible paths does not preclude advocacy for higher budgets.

The analysis and methods developed here serve as a counter-point to the notion that life cycle cost analysis is counter-productive, or that there are too many long-term uncertainties to provide value, or that insights are not actionable. Long-term life cycle cost analysis for NASA human space exploration is useful once a variety of more certain cost elements and budgetary outlooks are combined with transformative steps to understand where NASA models say 'yes'. This is possible even within limited (historical) budget prospects. The transformation required is informed and sanity-checked by the historical performance from recent public private partnerships and commercial services for delivering cargo and crew to the ISS.

Recommendation: Reconnaissance can and should look at many, different space exploration scenarios. Reconnaissance is useful, especially in difficult times, and especially as it costs very little to look at a large array of possibilities. There is enough more certain, or at least better understood elements in life cycle planning, to develop analysis that gives a very good idea of what lies around the basecamp in different directions. Best practice *delays* design decisions as long as possible⁷³, looking at all the possible options to gather knowledge and develop a business case.

2. Do all of our models still say 'no'?

No. Some of our models say 'yes'. To the degree it's ground-ruled in that transformation is permitted and possible for elements in the NASA space exploration and operations portfolio, the models say 'yes' even more. To the extent that space flight does not repeat the recent successes in commercial partnerships, the models will continue to say 'no', with wishful expectations about future budgets and costs passing as planning.

There is ample work in this field of quantitative life cycle cost analysis for NASA's space exploration scenarios, with assumptions (and advocacy) about budgets growing faster than inflation⁷⁴, among other generous affordability considerations. The work here serves as the other bookend, exploring scenarios without the usual generous affordability considerations, where NASA space exploration succeeds to the degree NASA transforms.

Barring an ability to transform, analysis shows that increasing space exploration ambitions squeezed under historical budget trends will cause a distribution of funding increasing NASA irrelevance. Reducing ambitions, aiming for closer targets, merely reinforces the irrelevance the new plan tries to avoid while creating unsustainable scenarios, programs stretched so far across time the low flight frequency calls into question the ability to maintain competence and safety. As well, irrelevance is the likely loss of stakeholder interest as much as a certainty of being overcome by events as planned results stretch beyond a generation.

Sustainable scenarios furthering human space exploration in relevant timeframes require a transformation of the NASA human space flight portfolio. The question of sustainability is especially important in the broader sense of the word – not just the narrow ability to survive or persist, but the ability to adapt, prosper and grow. The models say 'yes' more to the degree that NASA human space flight transforms it's approach to the exploration elements required. Given a potential, continuing loss of purchase power over time, staying ahead of the budget curve requires steps toward *partners, investment and services* and away from the traditional *contractor, development and acquisition* paradigm.

The alternative is to reduce ambitions, or if maintaining ambitions, to stretch these over timeframes so long that irrelevance is the only likely outcome.

Irrelevance is a useful surrogate for considering if a scenario is sustainable, stretching so far across time that even when adding up in analysis, it's unlikely anyone would ever see the scenario play out. Being overcome by events the longer a schedule stretches, losing stakeholders, or just losing stakeholder interest, being unable to transform to make up for lost purchase power, and flight rates so low that competency is lost and safety compromised, are real risks in a plan that might seemingly add up, but takes so long it's likely all irrelevant.

Recommendation: We propose a steady transformation of NASA space exploration and operations funding towards more, smaller commercial / public-private partnerships, favoring those with strong non-government business cases, to increase the pace of NASA achievements and avoid having most funding in projects with goals forever a generation away. Transformation, unlike the magic-bullet assumption of budget increases sustained over decades, can take small steps, with some potential examples shown in the hybrid scenarios explored here.

Even as actionable long-term plans may not be possible, given a lack of new large-scale fund lines in the space flight budget, scenario analysis should inform smaller investments, design trades and an overall sense of direction. Especially important is locating the intersection between possible NASA needs and private sector business plans, analysis that takes relatively little resources to explore. Best practice in any design trades and analysis should avoid favoring (or even seeming to favor) any point design or acquisition approach. The output of a trade space exercise should be an assortment of technology and concepts covering the bounds of what is possible. The most valuable outputs of a trade-space exercise help understand the boundaries of the trade-space – without making a down select that precludes long term possibilities.

Where quantitative scenario analysis is not possible, we recommend *scenario planning* - a qualitative technique that can mature a common understanding among stakeholders about the situation at hand. Rather than focusing on point-designs, usually favored by one or another stakeholder, many stakeholders must develop a common understanding about the future. This is especially so for questions beyond sustainment as survival, getting into matters of growth. While endless mitigation will refine and move around slices in a pie to live to fight another day, scenario planning that accepts a diversity of possible futures can get at the crux of the matter – growing the pie, transforming it and reinventing the pieces to be relevant to a new generation. Quantitative life cycle cost analysis as explored here can complement qualitative assessments, similarly avoiding blinders justified under guise of uncertainty. The task is to understand uncertainties, not run from them.

In closing, dramatic shifts in NASA's space exploration and operations portfolio could move exploration outcomes a generation to the left, into the realm of soon versus someday – but the notion has to be ground-ruled in that such wholesale change is possible and permissible.

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